Scale Up of Coated Conductor Technology at SuperPower

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- Jodi Reeves
- Dean Peterson, Los Alamos National Laboratory

HTS Solutions for a New Dimension in Power

Objective of Program

<u>Objective</u> : Scale up Coated Conductor processes to produce tape in piece-lengths greater than 1 km with performance greater than 100,000 A-m by mid-decade.

<u>Current Approaches</u> :
IBAD for buffer
MOCVD & PLD for HTS

Emphasis is on establishing

- Equipment & processes suitable for long production runs
- High throughput processes
- Continuous reel-to-reel on-line & off-line QC, &
- Robust manufacturing process for a practical conductor

How long would it take to produce 1 km?

For a low-cost conductor, high throughput is a major requirement.

Throughput **=**

Deposition Rate × Deposition zone length × Deposition zone width

Single-piece length **=**

Deposition Rate × Deposition zone length

Process	*Deposition Rate for $J_c > 1\ MA/cm^2$ (Angstroms/second)*
PLD	650
MOCVD	150
E-beam BaF_2	1
MOD	1

Hours to produce 1 km of HTS tape

1 micron thick HTS	Deposition Zone	
Deposition Rate	**1 m**	**10 m**
150 Angstroms/s	**18**	**2**
1 Angstrom/s	**2,778**	**278**
10 Angstrom/s	**278**	**28**

Only MOCVD offers advantage of BOTH high deposition rate & large deposition area

Process	*Deposition Rate*	*Deposition Area*
PLD	High	Small
MOD	Low	Large
E-beam BaF_2	Low	Large
MOCVD	**High**	**Large**

Throughput = Deposition Rate x Deposition Area

***Unlimited* Deposition Area with MOCVD :**

As long & as wide as showerhead

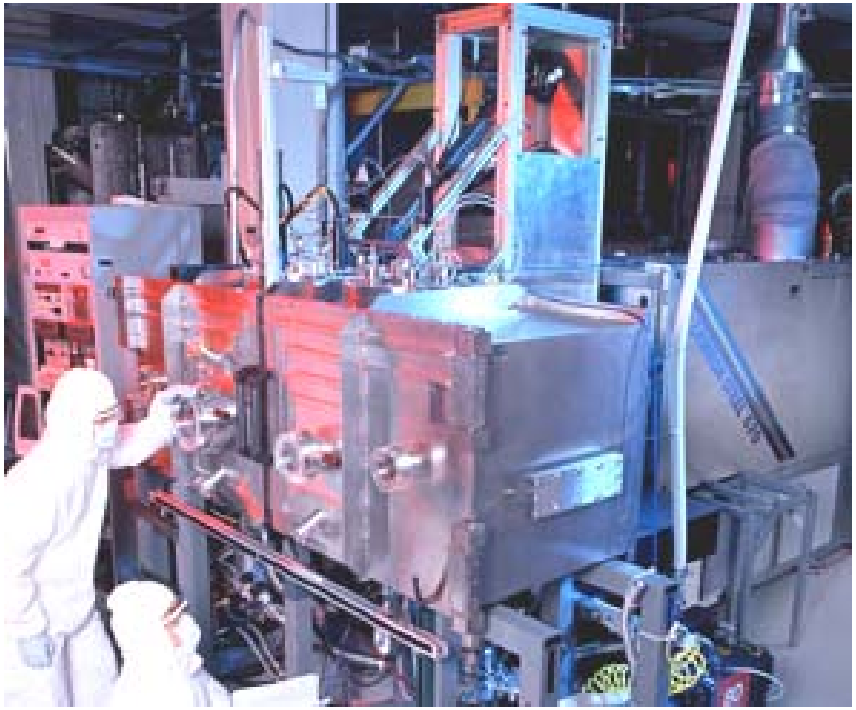
A wide tape can be processed and slit into numerous 4 mm wide tapes

Intermagnetics is strongly committed to SuperPower's Coated Conductor program

Pilot scale facilities established for coated conductor fabrication in a Class 10000 cleanroom

Additional pilot-scale facilities are being added.

Two-thirds of R&D funding & 100% of capital equipment funding in FY'03 was provided by Intermagnetics



In addition to DOE, this program was supported by ….

U.S. Air Force : Dual Use Science & Technology Program

Air Force Office of Scientific Research

New York State Energy Research & Development Authority

Outline

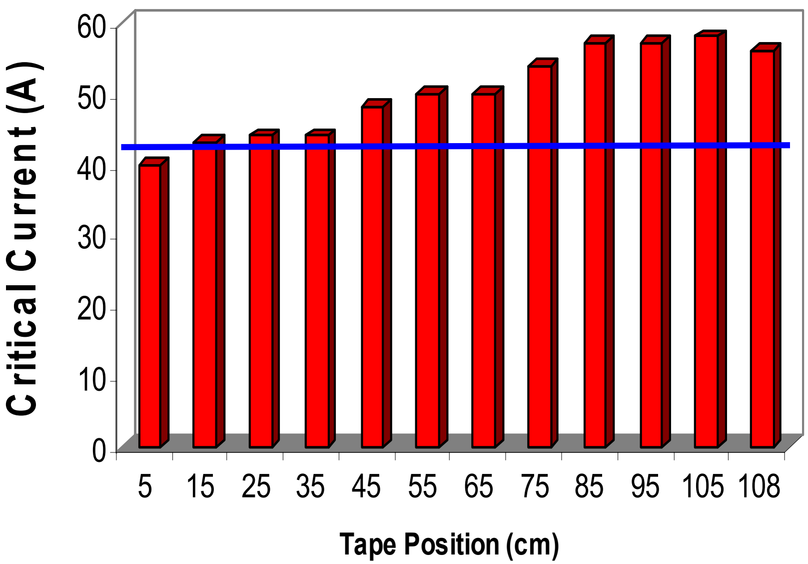
1. Performance enhancement in meter-lengths	Jodi Reeves
2. Quality Control for long length processing	Jodi Reeves
3. Developments in high-throughput processing	Selva
4. Processing of longer lengths	Selva
5. Practical Conductor Development	Selva
6. Technology Transition	Dean Peterson
7. Summary	Selva

Performance enhancement in meter-lengths

Status at last DOE Peer Review

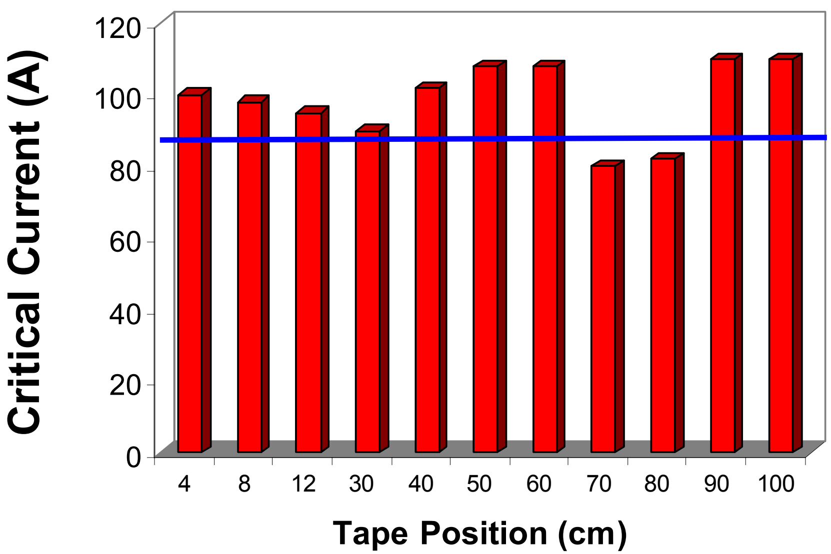
We had begun processing of 1 m tapes by PLD & MOCVD

PLD



43 A over 1 m

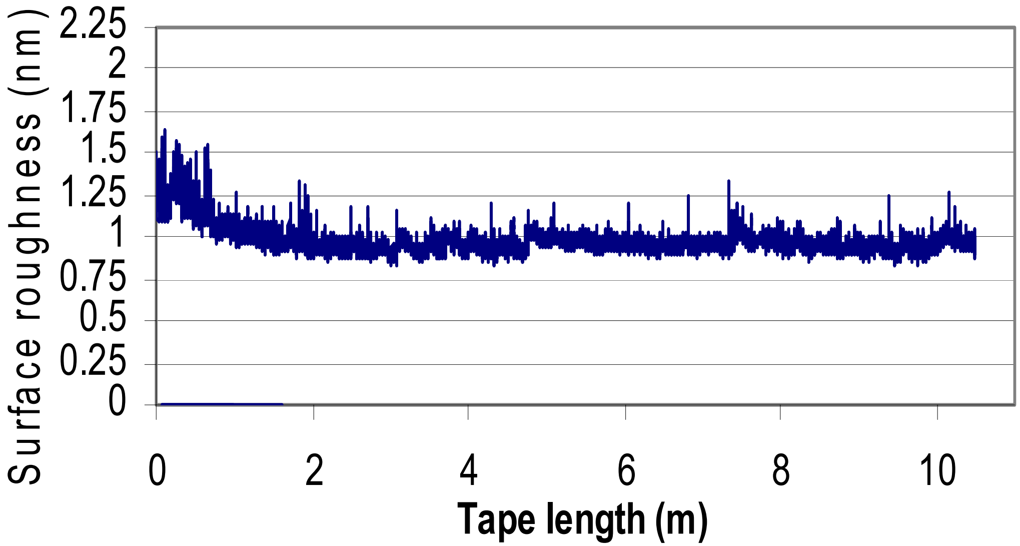
MOCVD



90 A over 1 m

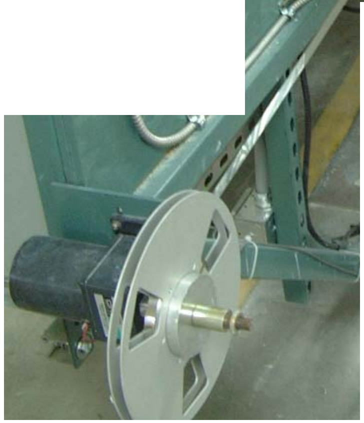
Our first action item after the Peer review last year was to achieve over 100 A in meter lengths

Did substrate quality affect tape performance in meter lengths ?



Av. roughness over 10 m = **<u>1 nm</u>**

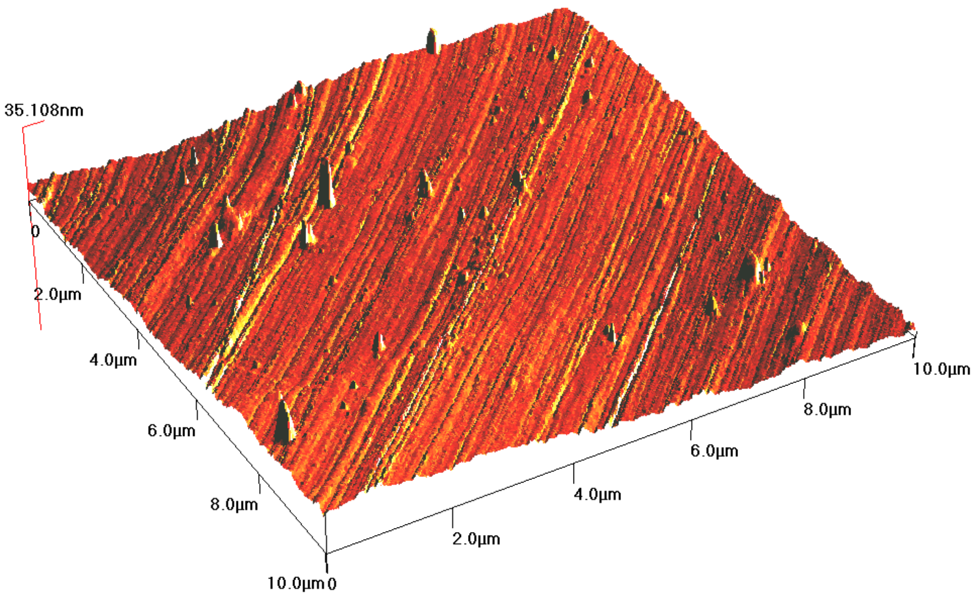
Std. deviation over 10 m = **<u>0.08 nm</u>**



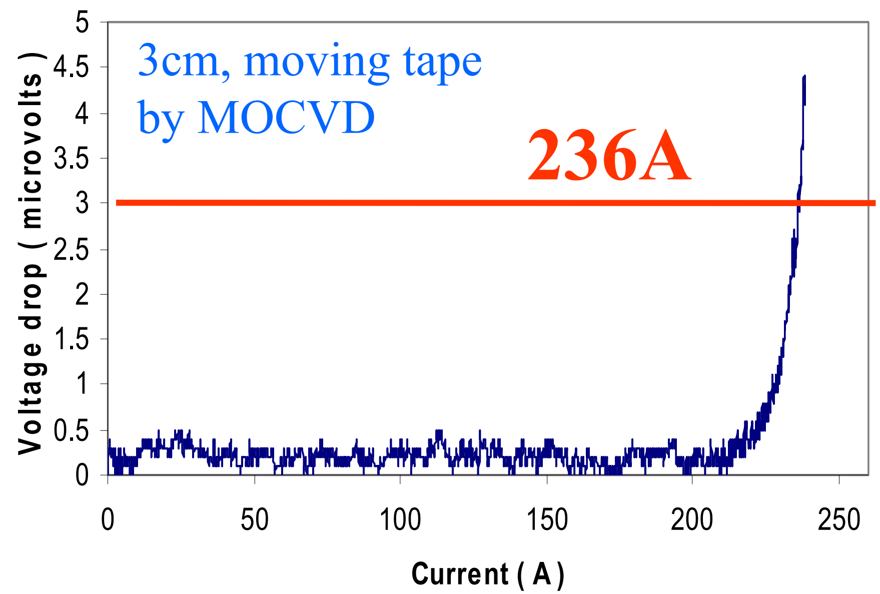
Chemical Mechanical Polishing rig

Substrate roughness is very small & uniform over long lengths

Substrate : Grooves are formed in the substrate polishing process, but do not appear to affect Jc

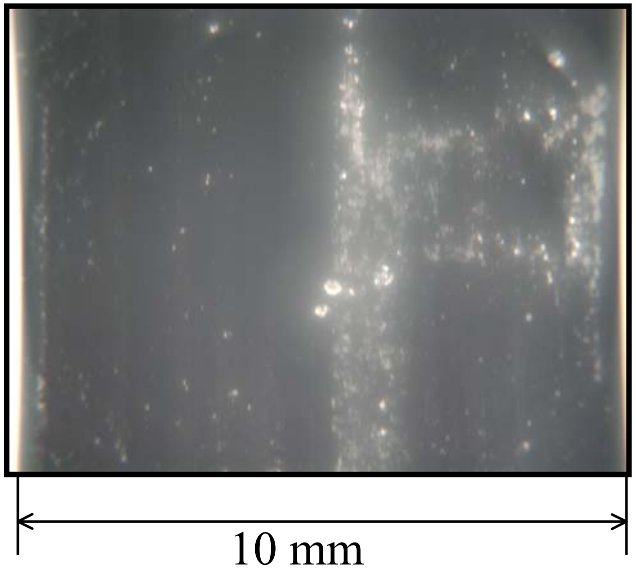


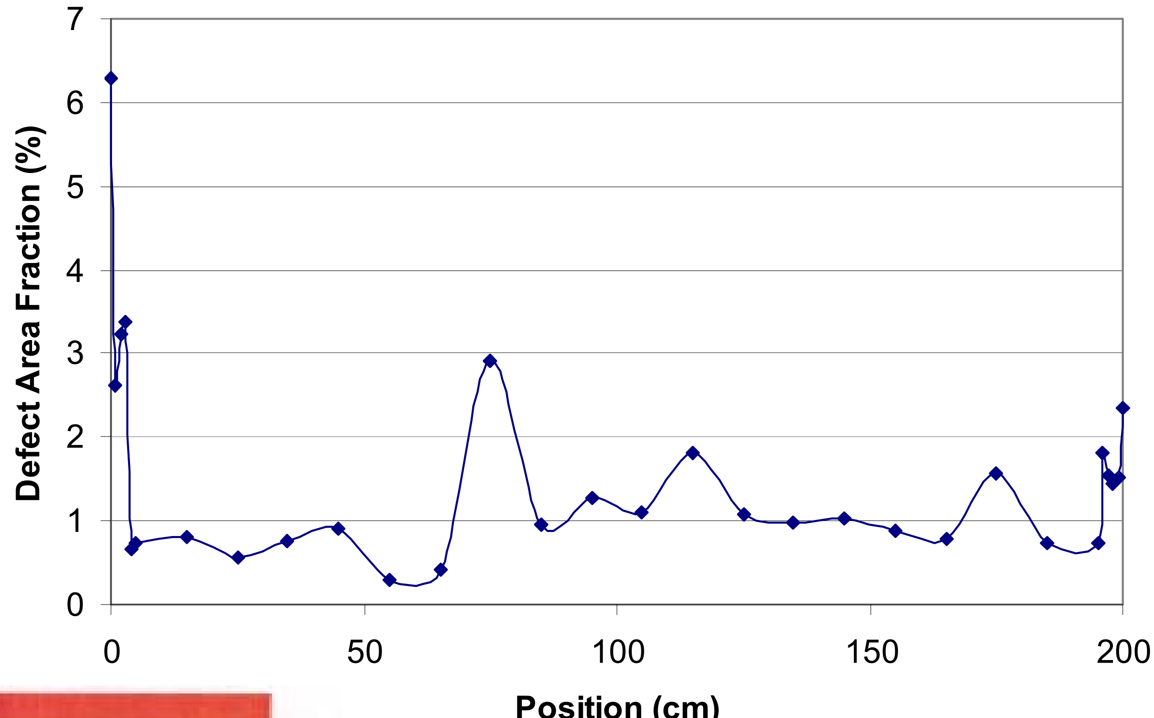
Grooves from Chemical Mechanical Polishing are ~100nm wide and 2-4nm deep….

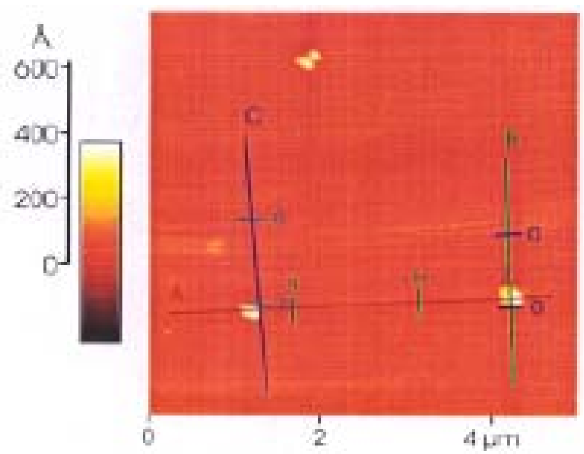


….but, High Ics were achieved in short samples on the Chemical Mechanically Polished substrates

Quantitative defect analysis of meter-long tapes is necessary since particles on the surface affect tape roughness.







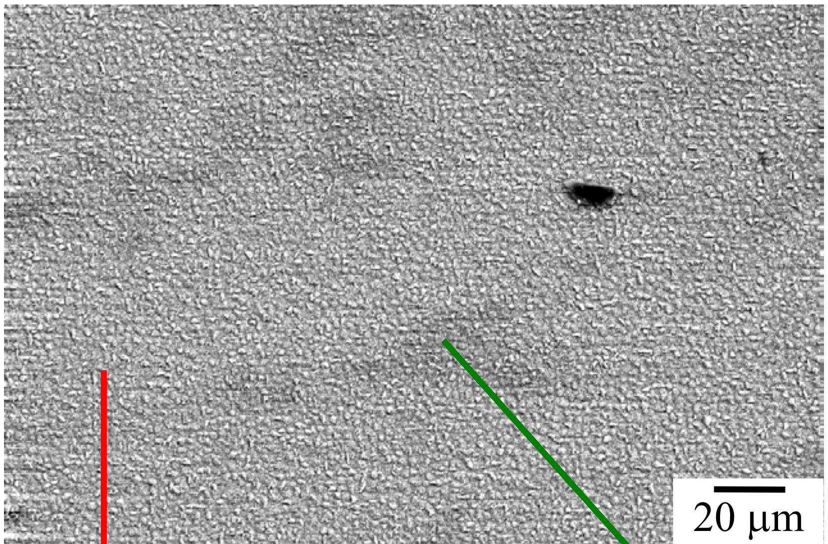
Line	R_a
A	64.6 Å
B	41.2 Å
C	9.69 Å

Paul Arendt

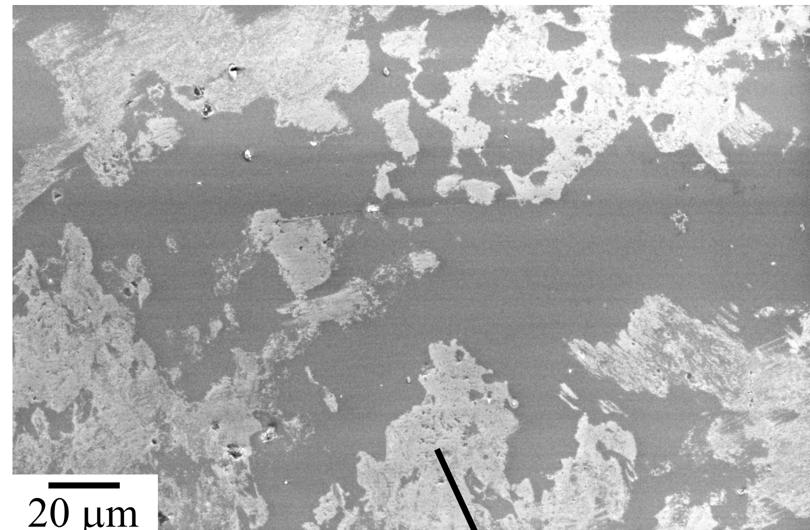
1943 - 2003
Los Alamos
NATIONAL LABORATORY

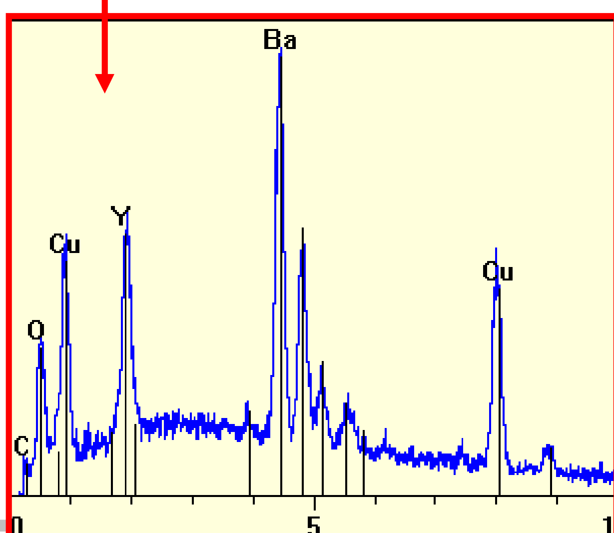
We identified defects in the HTS film that limited performance.

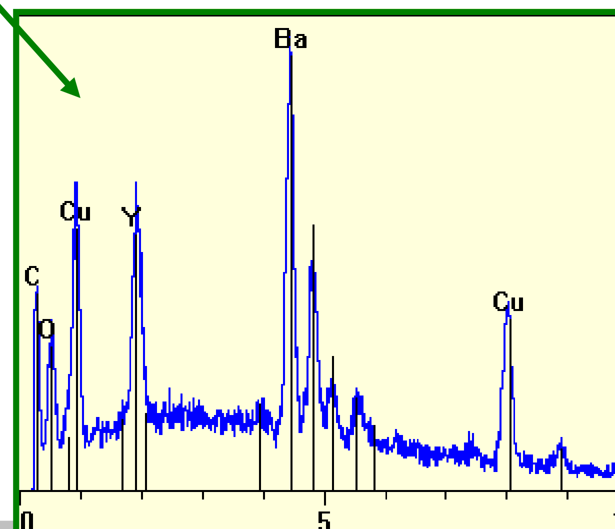
YBCO



buffer

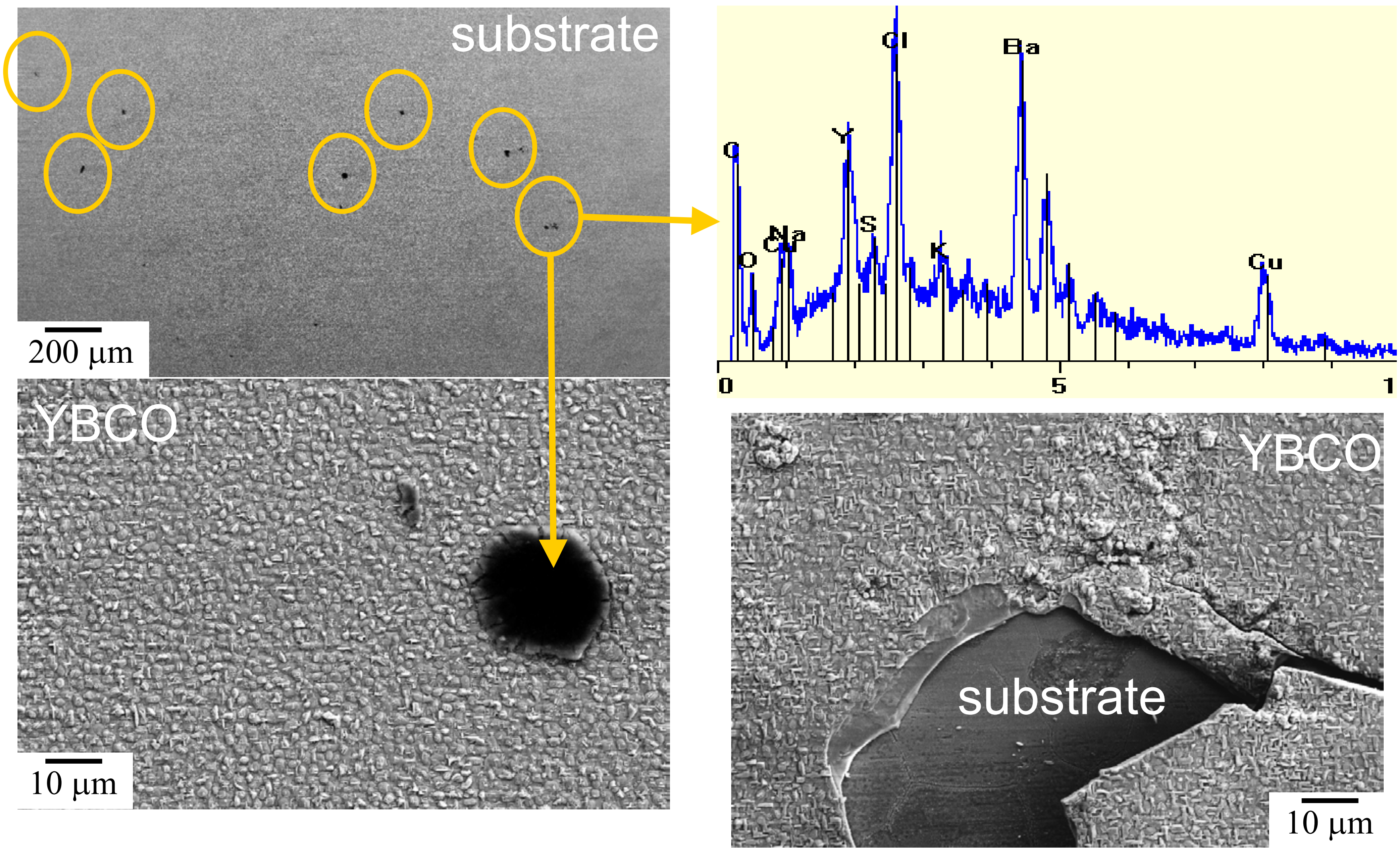






Traced back oily contamination to the unpolished metal tape from the vendor.

Particles and contamination on the substrate caused defects in the YBCO and delamination of the buffer.

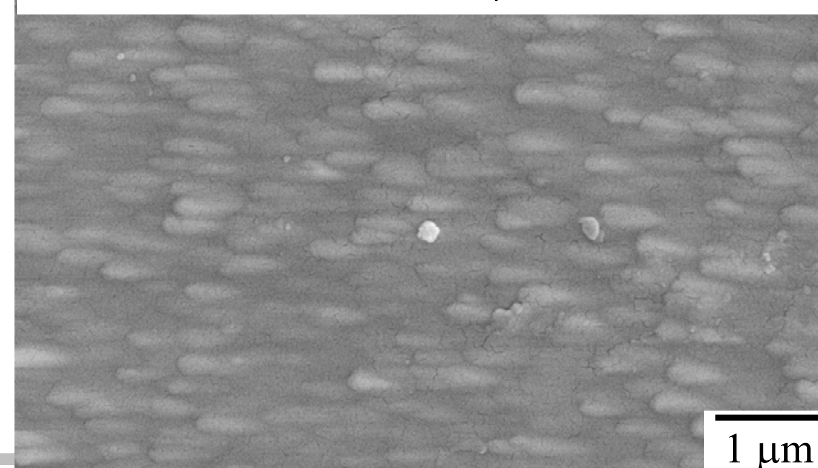


IBAD : Increasing substrate etching time degrades texture and surface morphology.

10min etch; $\Delta\phi$=11.8º

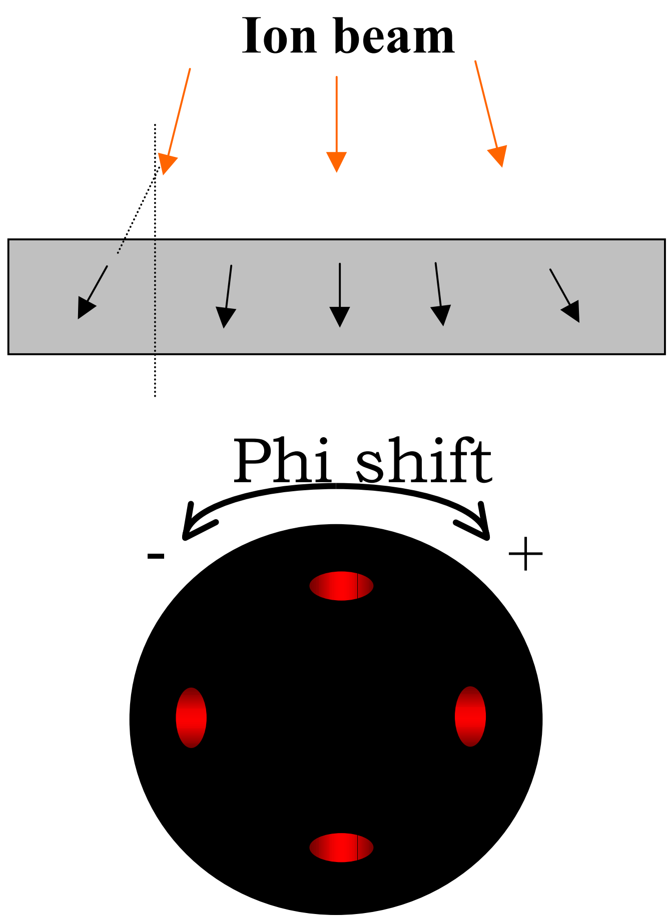
20min etch; $\Delta\phi$=12.2º

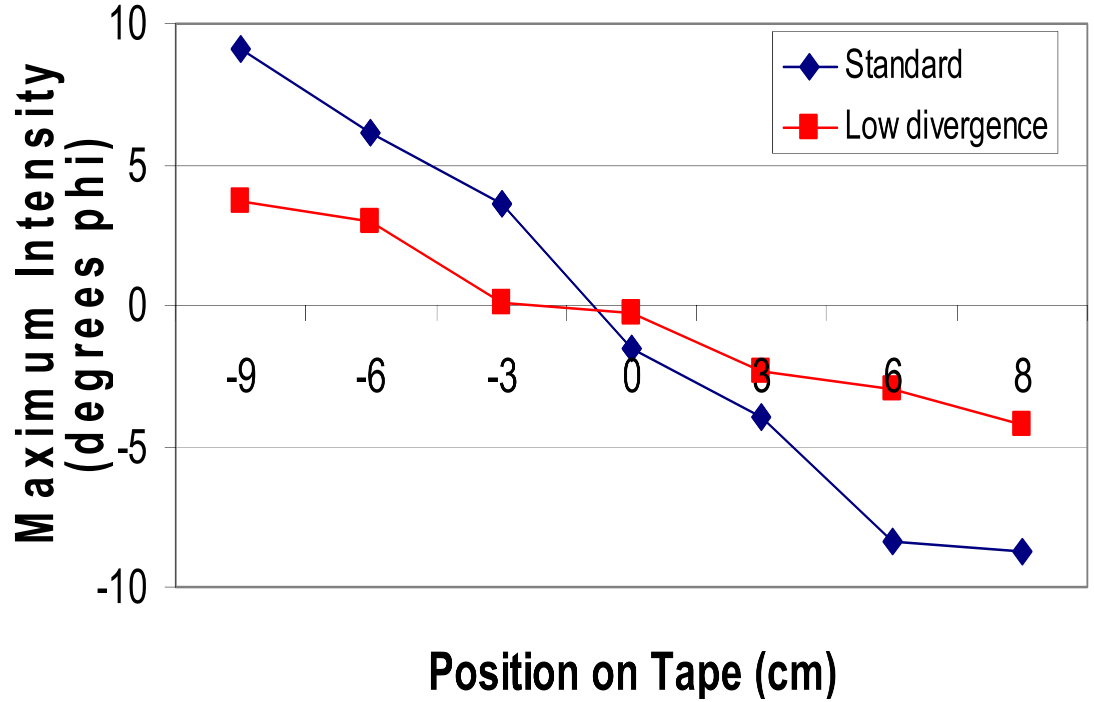
40min etch; $\Delta\phi$=13.8º



I_c decreases by 10% when the substrate etch time is increased from 10 to 40 minutes.

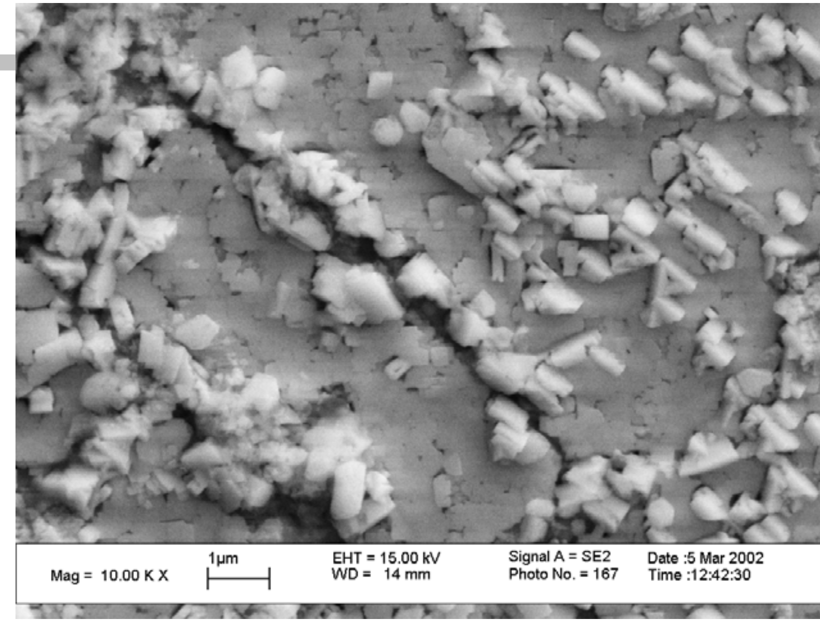
IBAD : Beam uniformity was improved by decreasing the beam divergence.





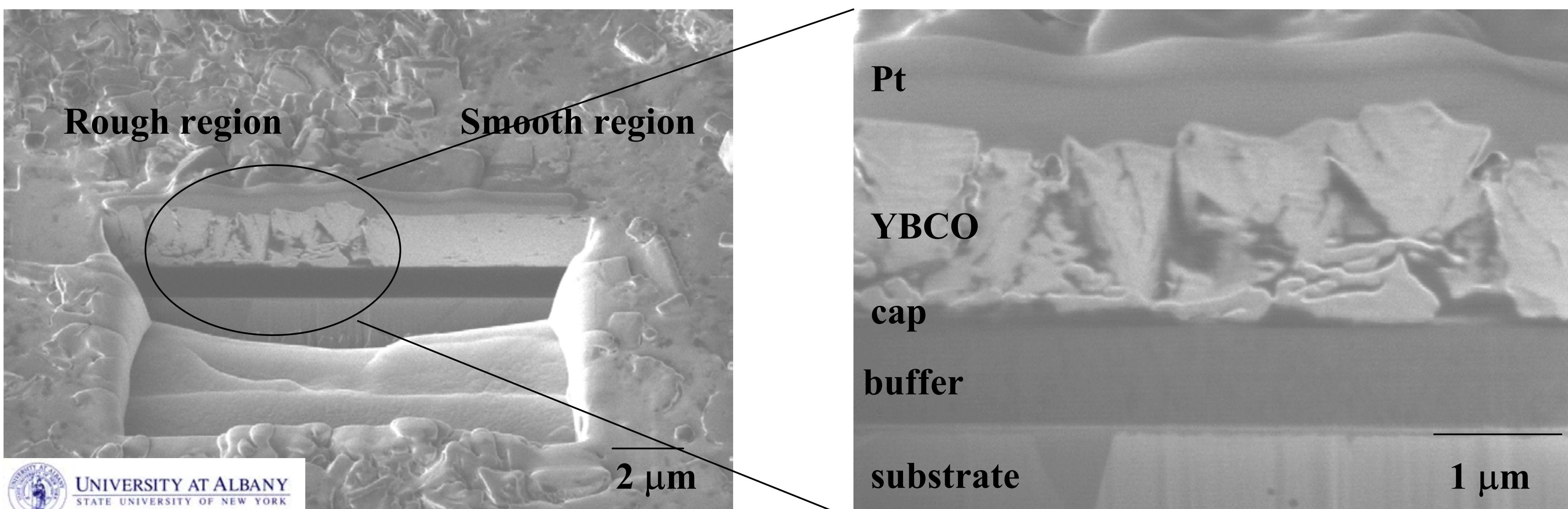
Phi shift was reduced by half in low divergence stationary runs. Best in-plane texture of 9 degrees obtained.

Cap Layer : Uniformity affects HTS layer



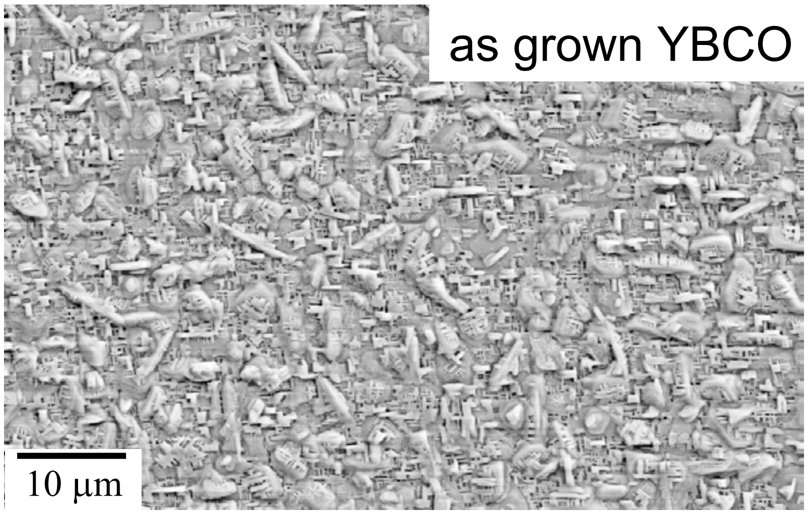
Non-optimum CeO_2 thickness can lead to defects such as cracks and misaligned grains in the YBCO layer.

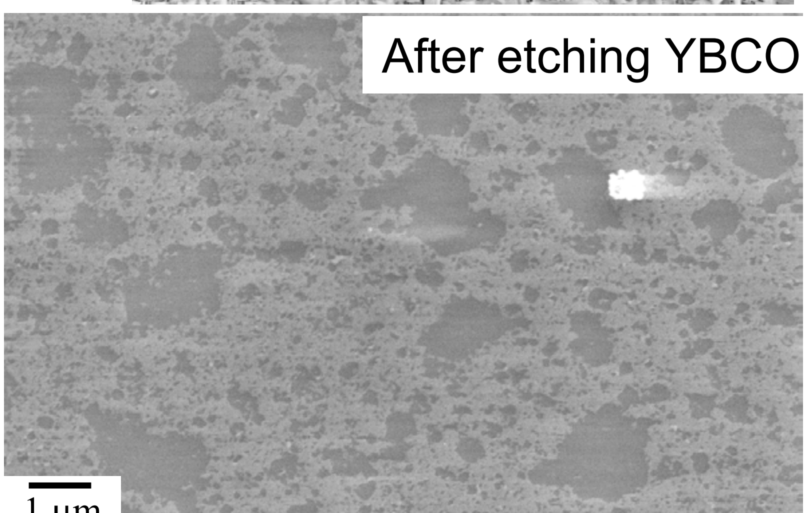
Non-uniform coverage can cause interface reactions between YBCO and CeO_2 and defects in the YBCO film



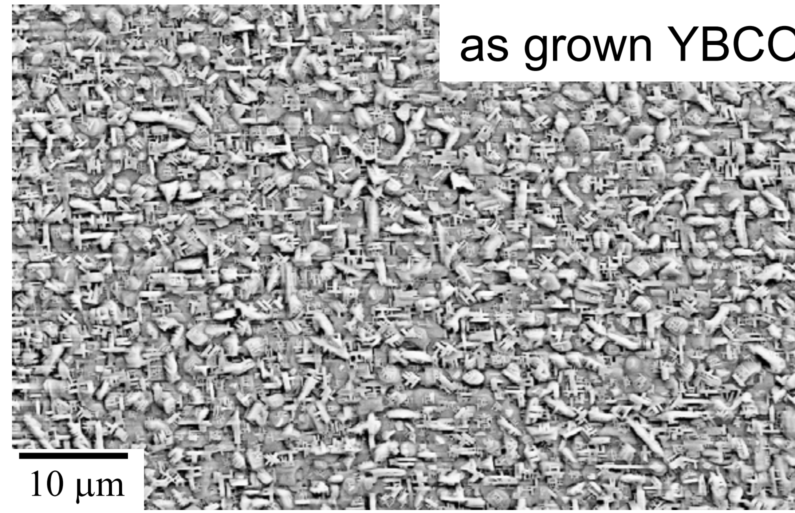
Cap layer uniformity is related to YBCO I_c

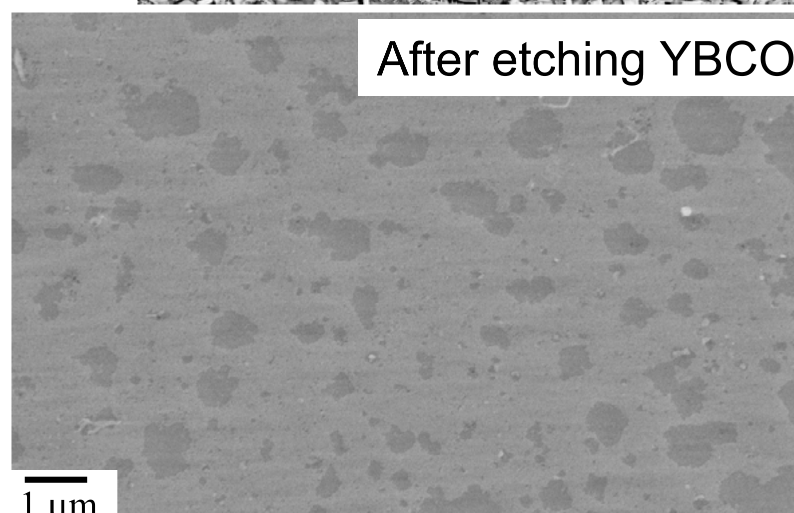
Ic = 51A





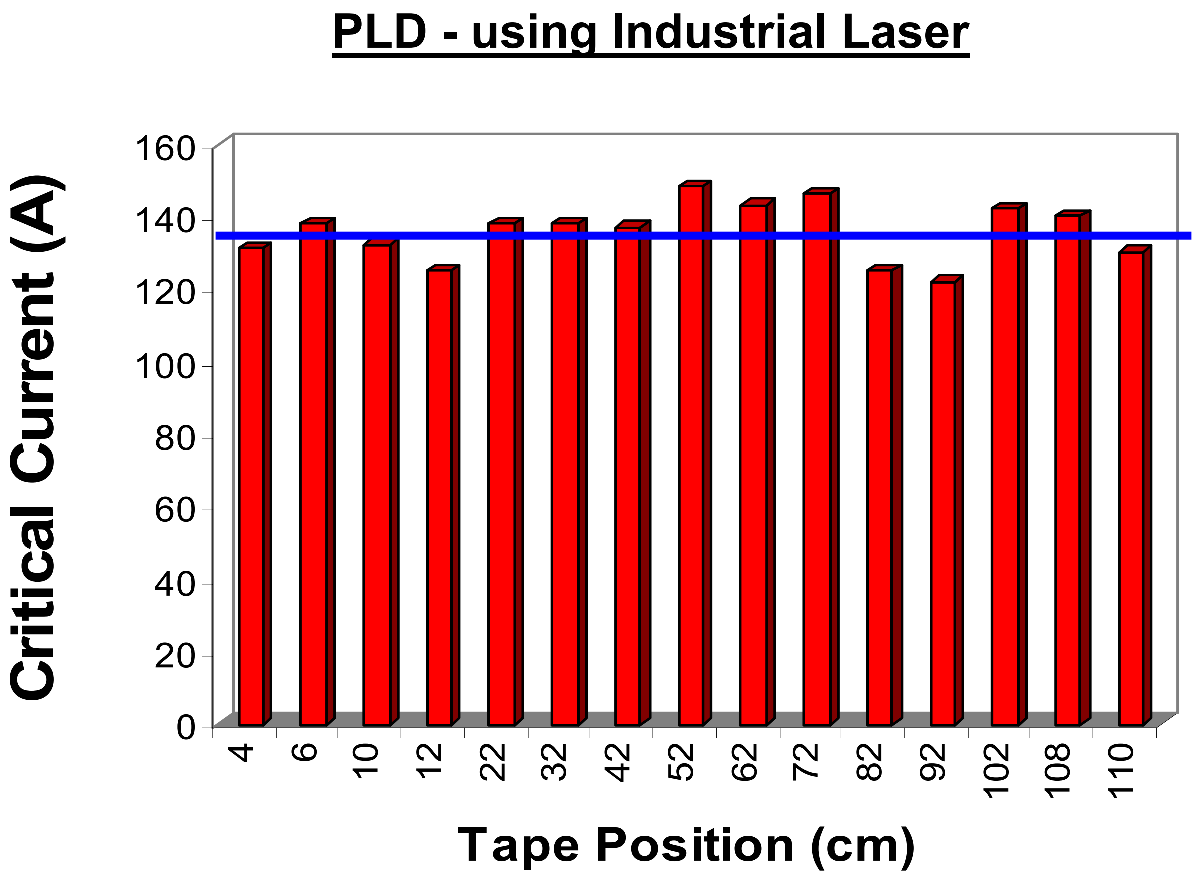
Ic = 104A





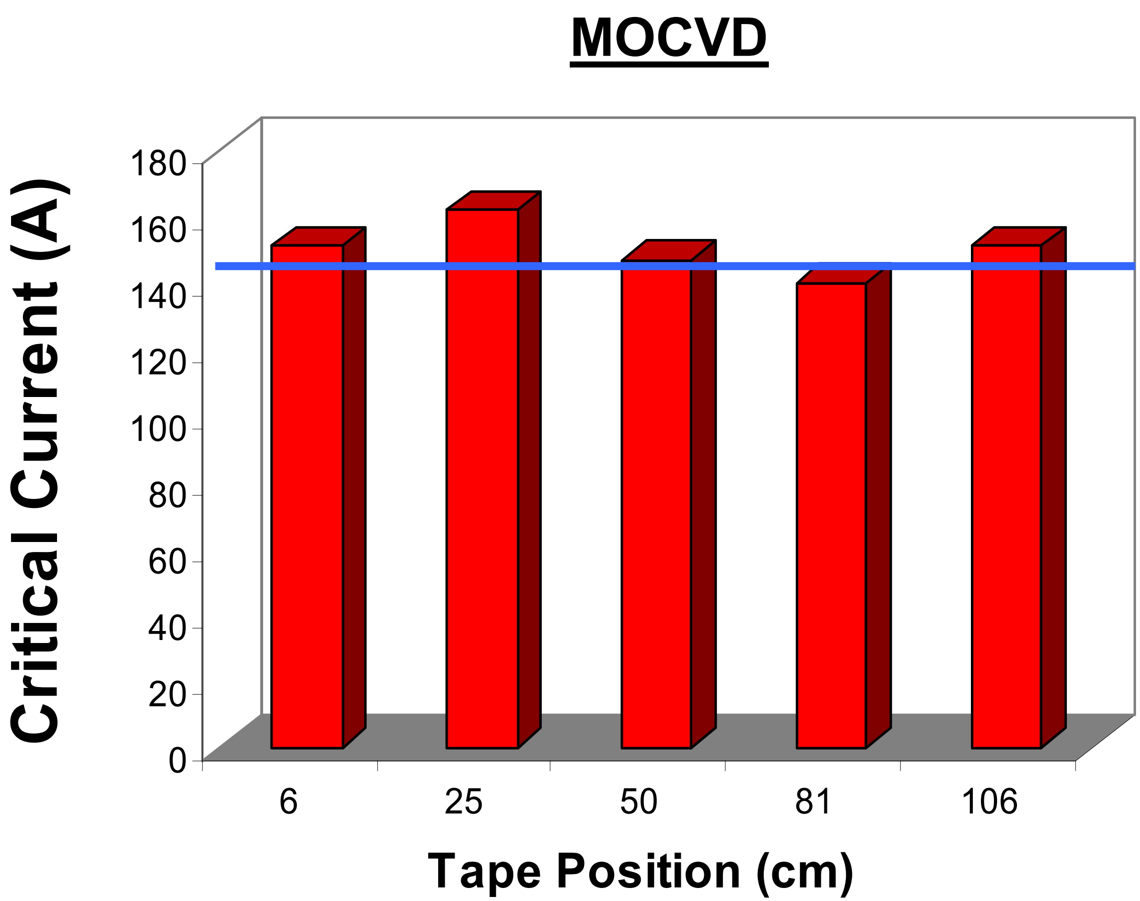
Improving quality of all processing steps led to 100+ A performance in meter lengths

SuperPower Inc.



In Oct. 2002, end-to-end Ic = 135 A over 1.1 m

100+ A over meter lengths was achieved with MOCVD too

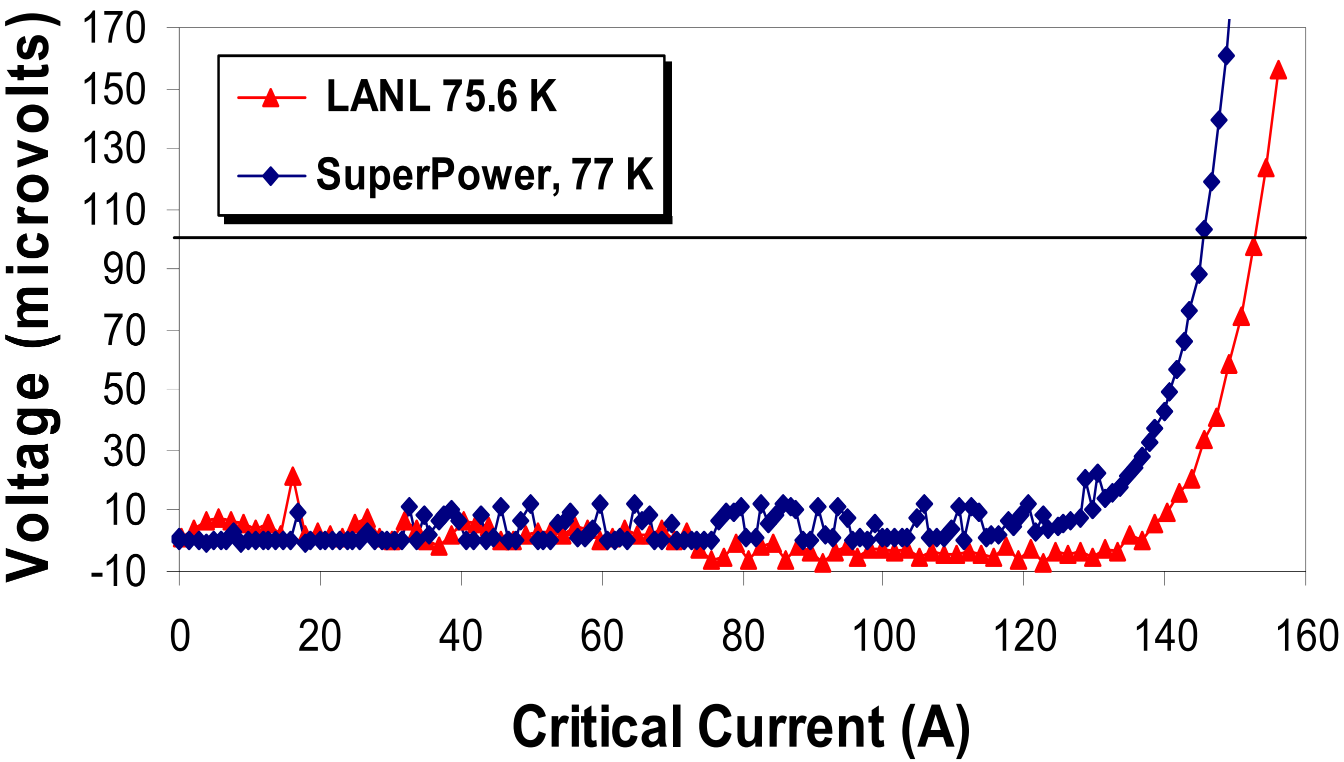


In Oct. 2002, 147 A over 1.06 m

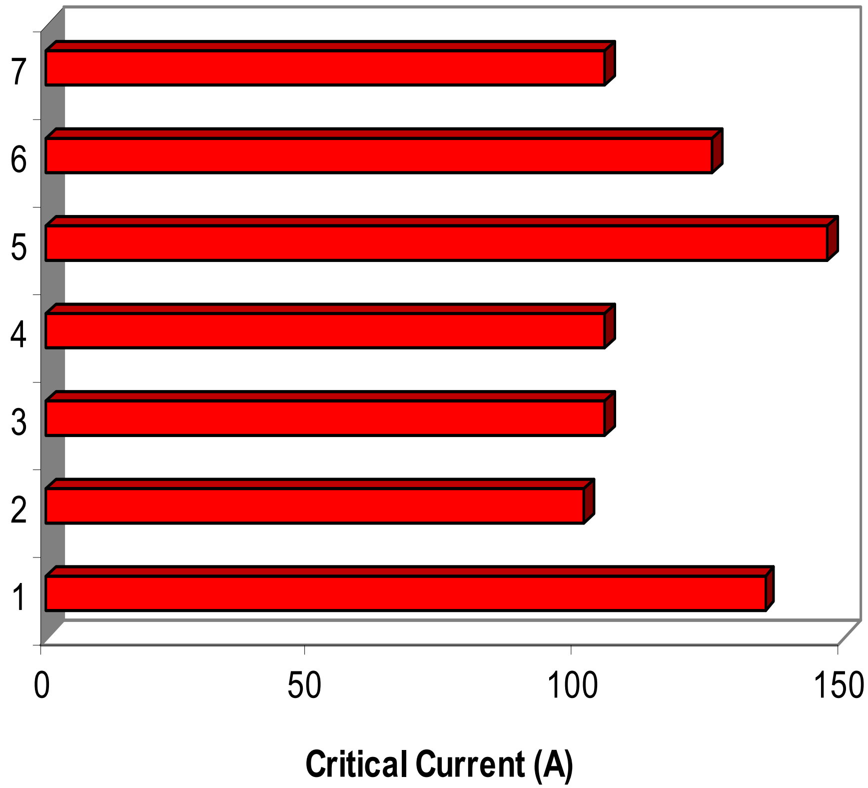
100+ A performance in meter-long tapes was verified at LANL

1.23 m section re-measured at SuperPower. Ic = 147 A **at 77 K**

Same 1.23 m section measured at LANL. Ic = 153 A **at 75.6 K**



100 A Class, Meter-long Coated Conductor tapes are routinely produced with both high deposition rate processes, PLD & MOCVD



MOCVD: 105 A over **2.8 m**

MOCVD: 125 A over 1.1 m

MOCVD: **147 A** over 1 m

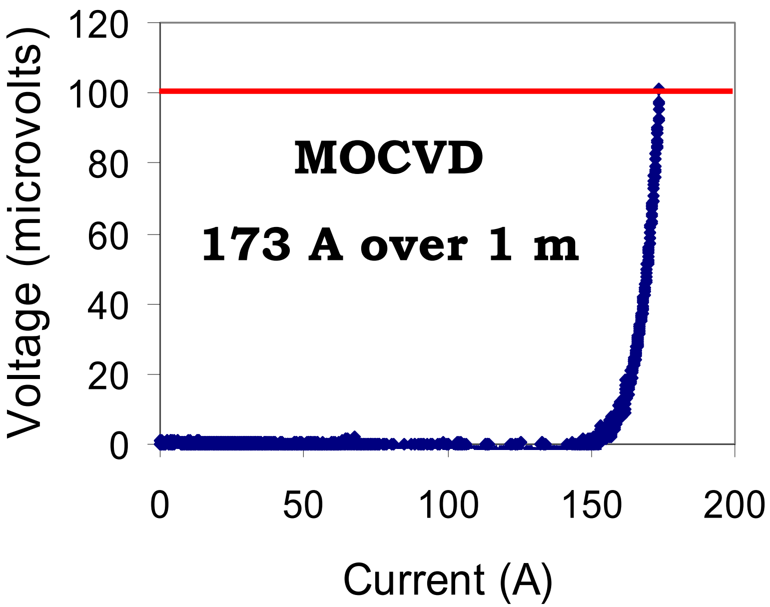
PLD: 105 A over **3.0 m**

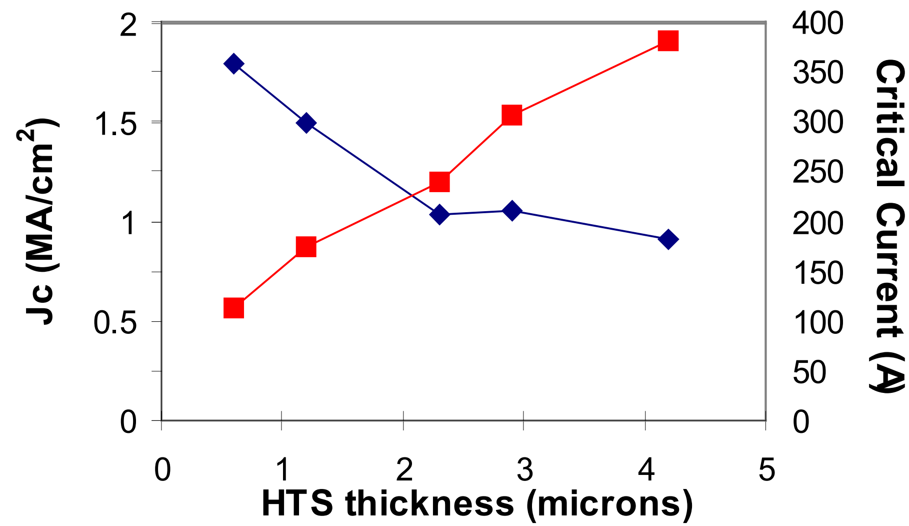
PLD: 105 A over 1.0 m

PLD: 101 A over 1.24 m

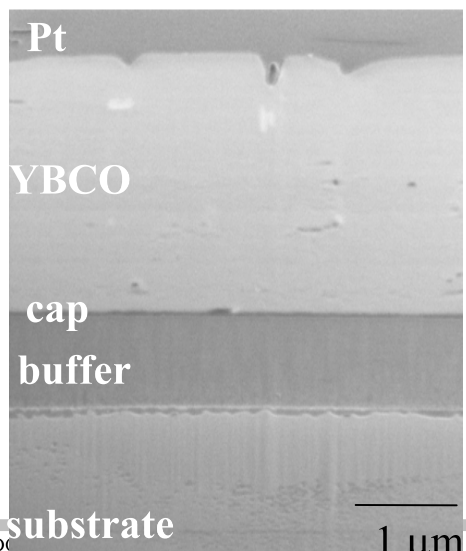
PLD: 135 A over 1.1 m

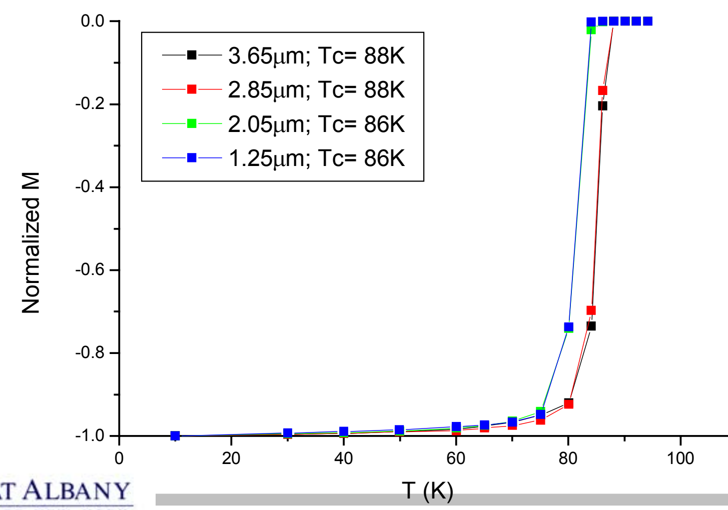
Higher currents achieved by MOCVD & PLD beyond routine 100 A





Ic = 380 A, Jc = 0.91 MA/cm² at 4.2 µm





University at Albany
State University of New York

<u>Next Step</u> : Produce longer lengths, but need to establish appropriate QC tools first

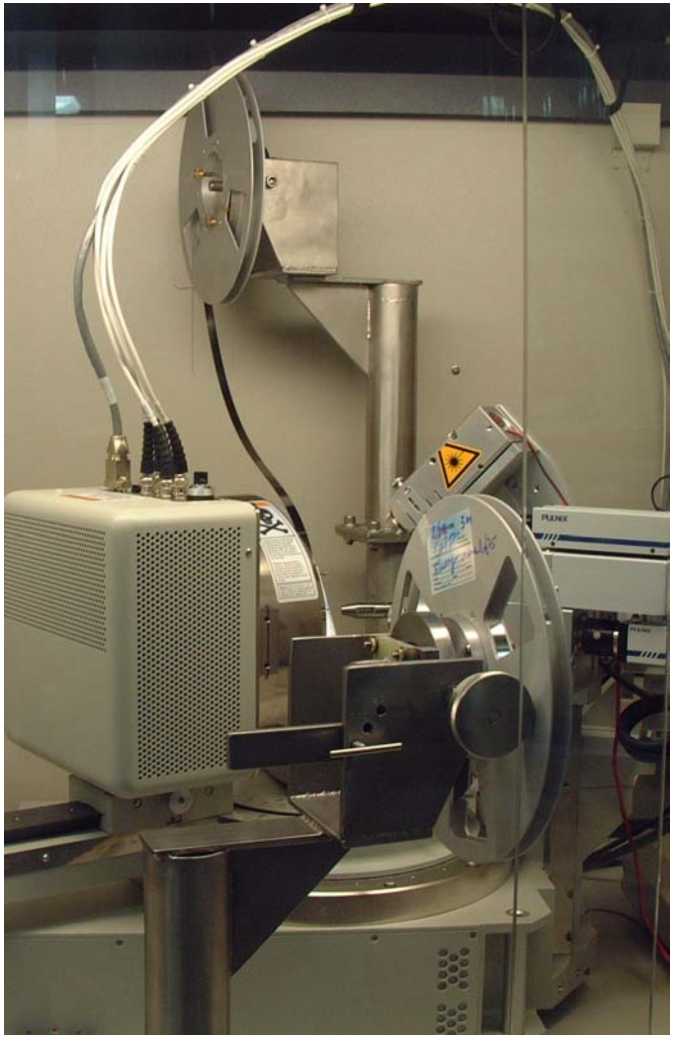
Reel-to-reel in-plane texture measurement

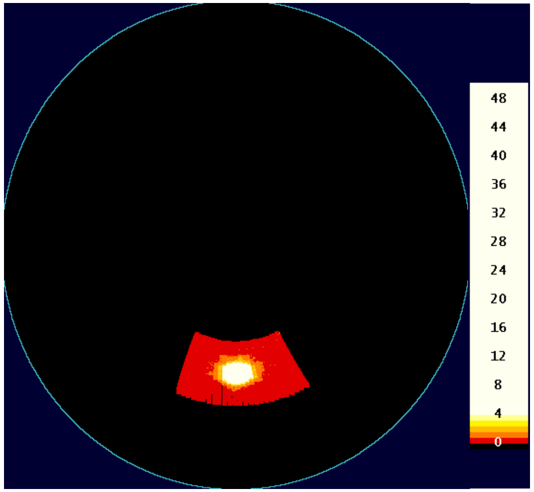
Reel-to-reel thickness, composition measurement

Reel-to-reel SEM

Reel-to-reel Raman Spectroscopy (with ANL)

Last year we showed modification of commercial XRD system for in-plane texture measurements on long IBAD tapes.



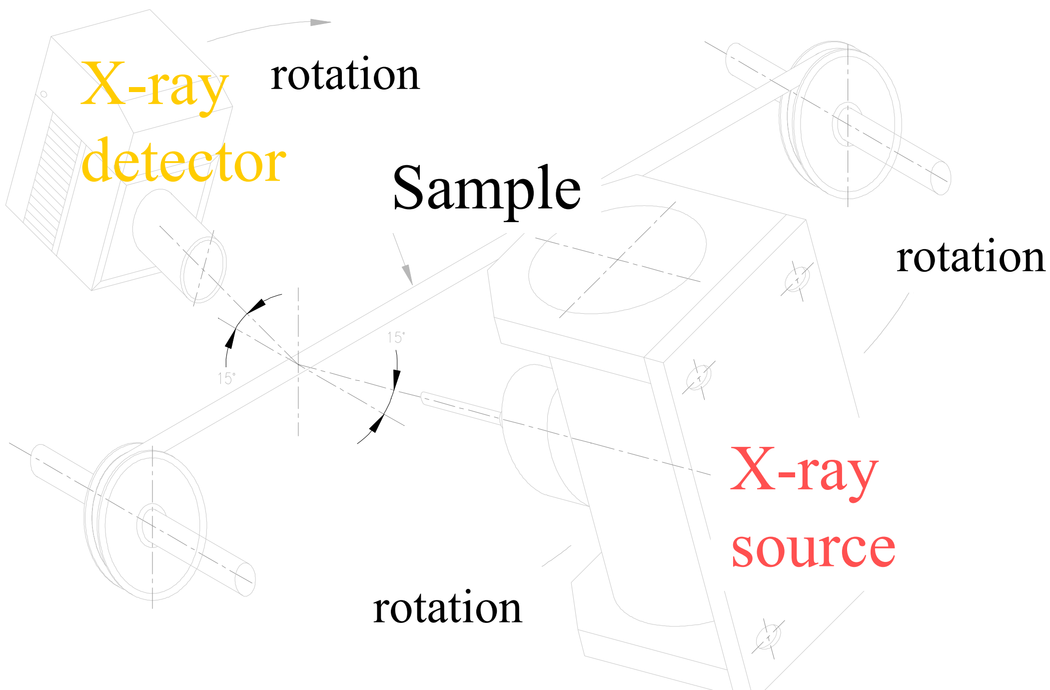


- While this system provided <u>direct</u> in-plane texture measurements in reel-to-reel mode, *<u>continuous</u>* tape movement was not possible.
- Measurement time for 1000 pole figures = 10.4 days (250 woman hours)!

Breakthrough design for RAPID, CONTINUOUS, IN-PLANE TEXTURE measurements for Coated Conductors

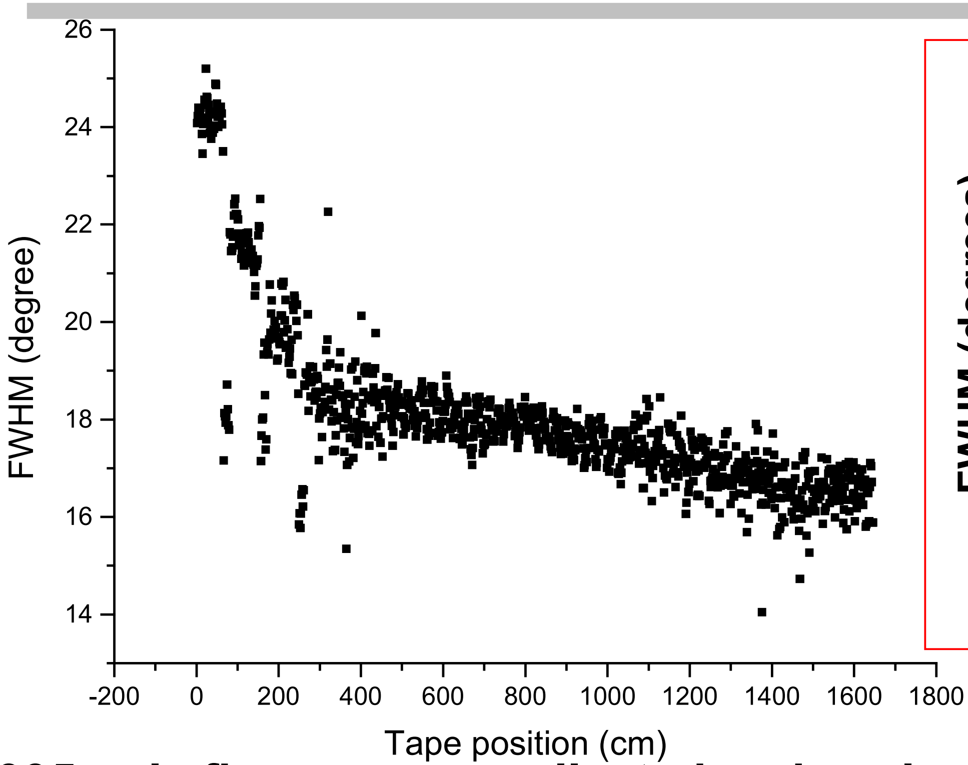
High intensity, low power, parallel beam x-ray source and fast, energy efficient x-ray detector will allow rapid reel-to-reel buffer layer texture analysis

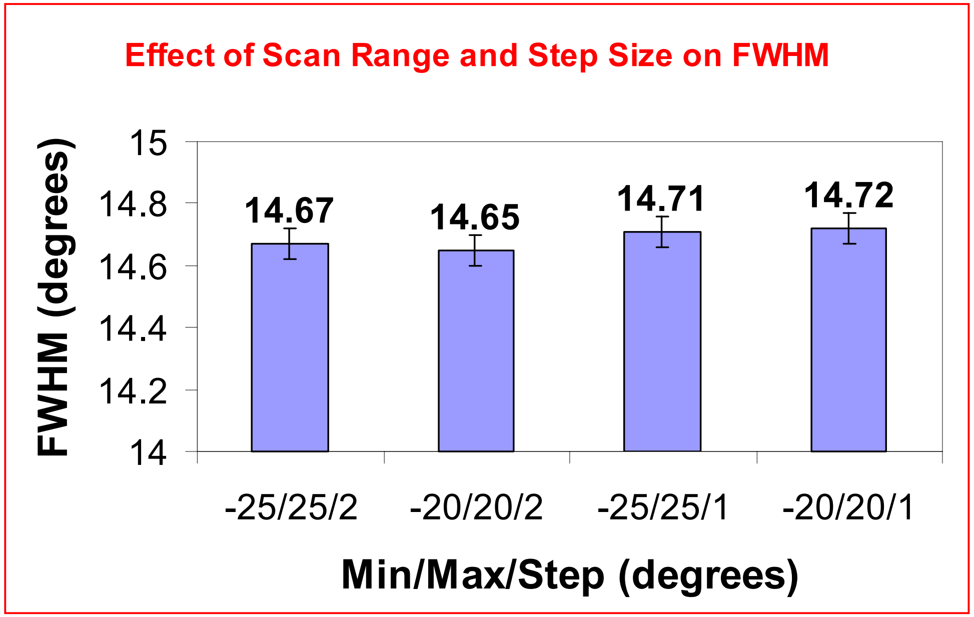
Design is suitable for <u>in-situ</u> process control too !



<u>Partners</u> : X-ray Optical Systems, Prof. Robert Snyder, Georgia Tech

Continuous, automatic, direct in-plane texture measurements over 16.5 m IBAD tape





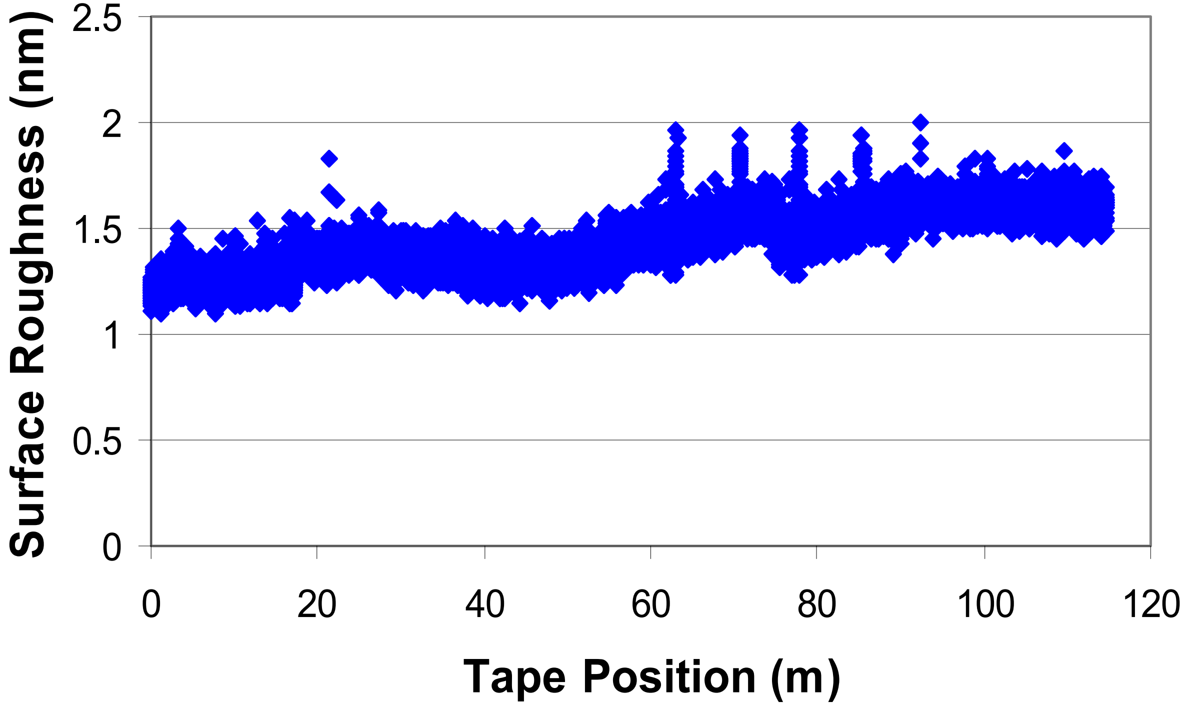
995 pole figures were collected and analyzed automatically in 46 hours (5 times faster than previously possible)

- scan range: -32 to +32° in phi with 1 degree step size
- acquisition time: 1 sec per point with detector averaging 5000cps
- cycle time for complete pole figure = 2.77 minutes (1.66cm tape travel)
- Cycle time can be improved to 1 minute by scanning over smaller phi range (± 20°) with 2° step size

Developments in High Throughput Processing

Single piece lengths of up to 170 m polished with uniform surface roughness using Chemical Mechanical Polishing

On-line surface roughness data taken every 2.5 mm



Average surface roughness over 116 m = 1.43 nm

Standard deviation = 9.3%

However, speed of the CMP process is low ~ 3 m/h

Verified LANL's electropolished substrate quality for our IBAD & MOCVD process

LANL demonstrated 10x higher throughput with electropolishing at DOE Peer Review in 2002.

Obtained electropolished substrate from LANL right afterwards

R_a of electropolished tape (measured at SuperPower) : 5 nm

Texture of IBAD layer (deposited at SuperPower) = <u>12.6°</u>

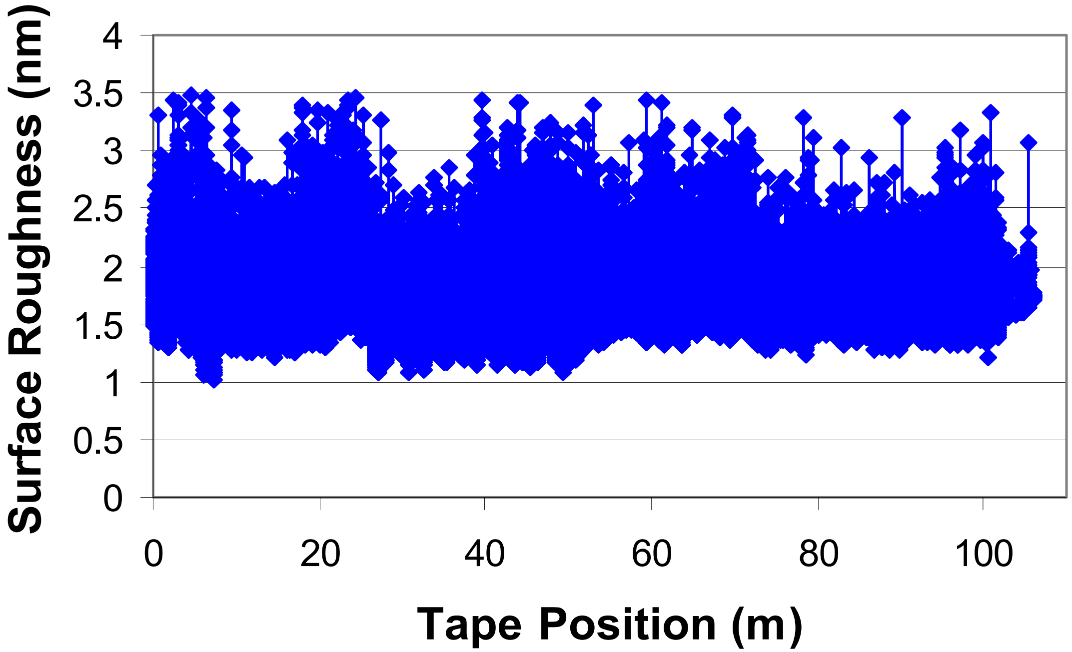
Performance of YBCO deposited by MOCVD at SuperPower on the buffered electropolished substrate :

I_c > 200A short sample

I_c= 173A over 1 meter

100 m electropolished tape produced

On-line surface roughness data every 1.8 mm

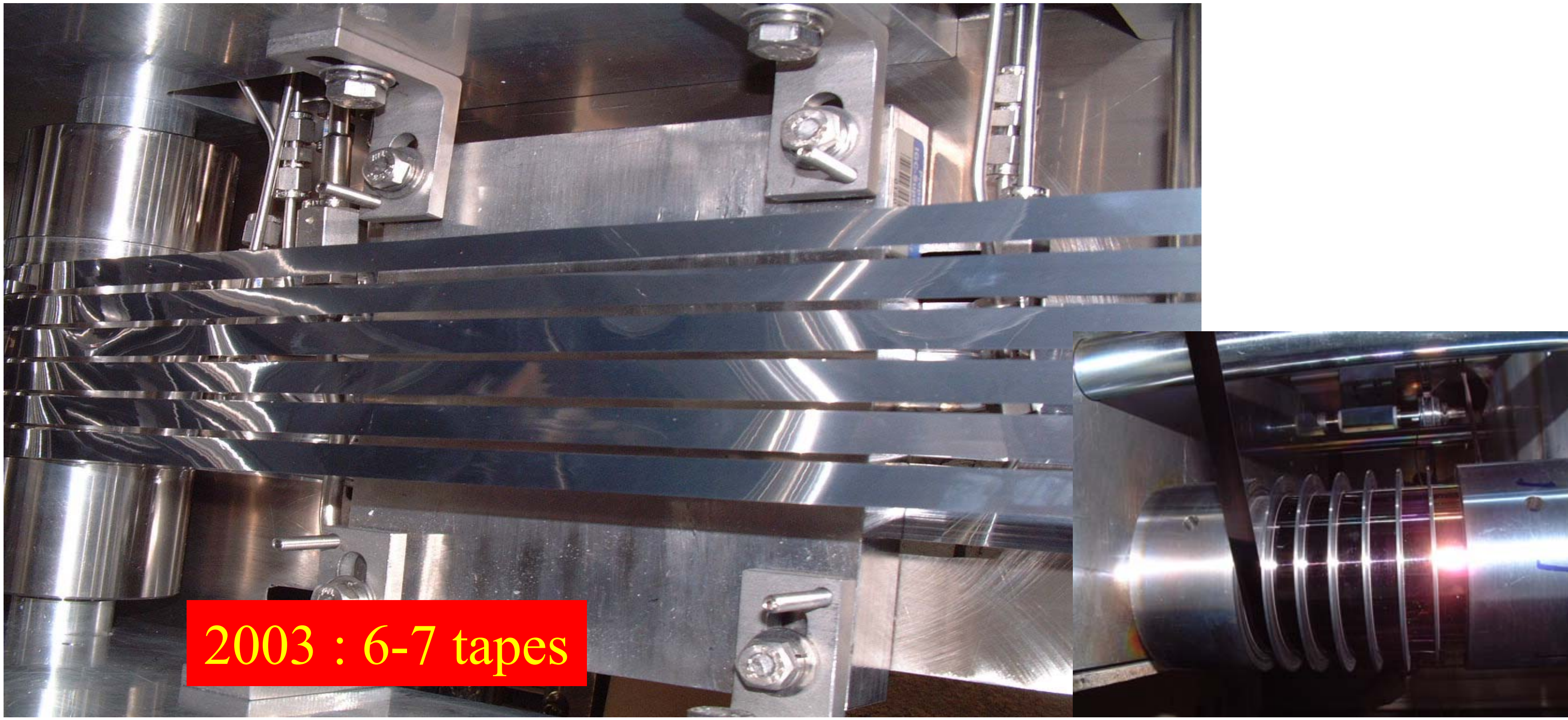


Average roughness over 100 m = 1.7 nm
Standard Deviation = 15%

Time to polish 100 m = 6 hours

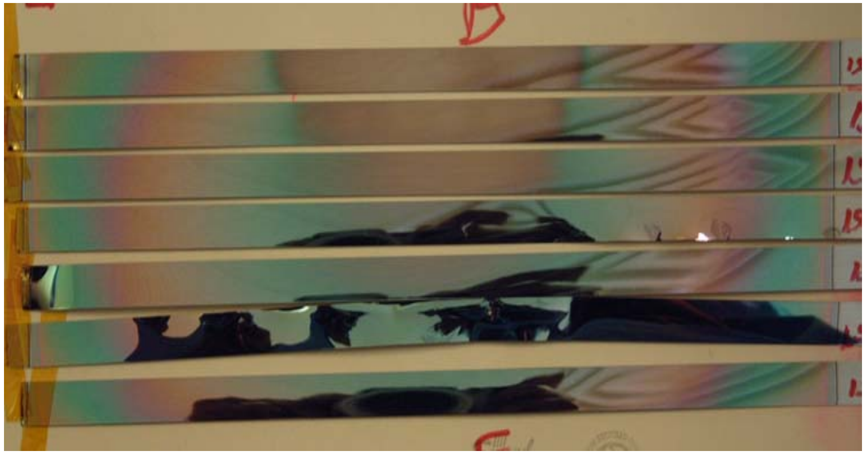
Helix system installed in Pilot IBAD facility for increased throughput

SuperPower Inc.

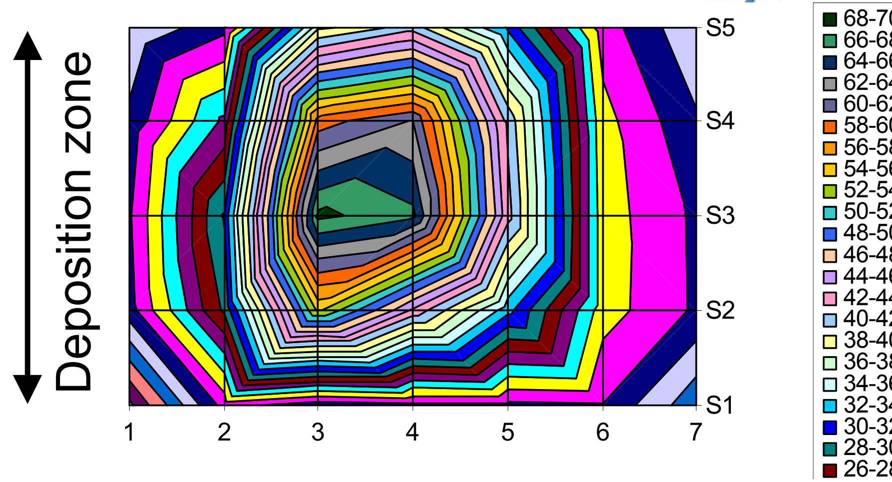


Single-piece length throughput Increase = 7x

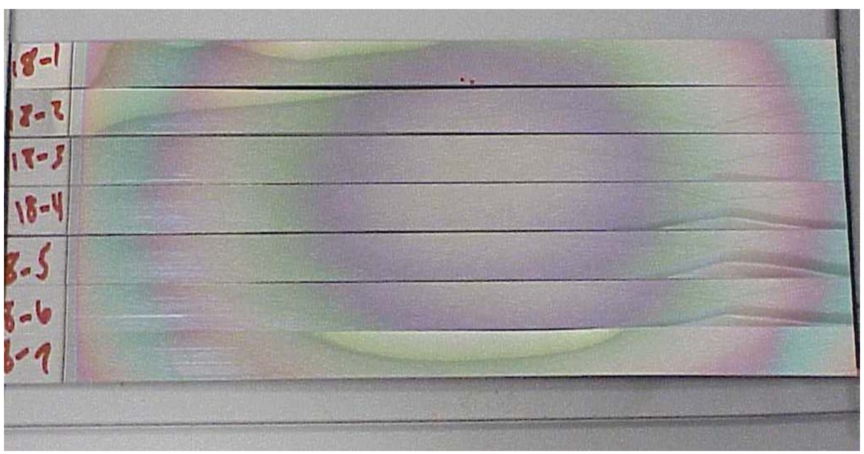
IBAD Process had to be optimized over a larger deposition zone of 7 tape wraps



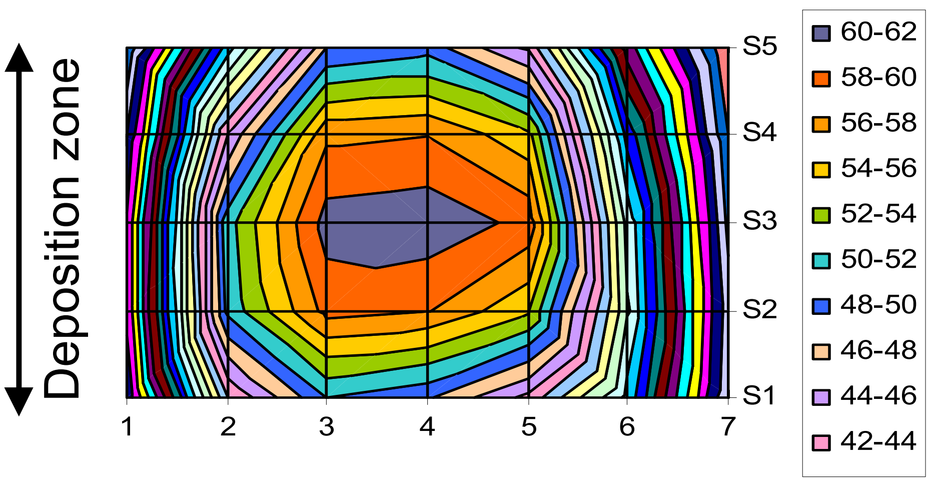
Deposition flux was off-centered



Ion beam profile was very non uniform

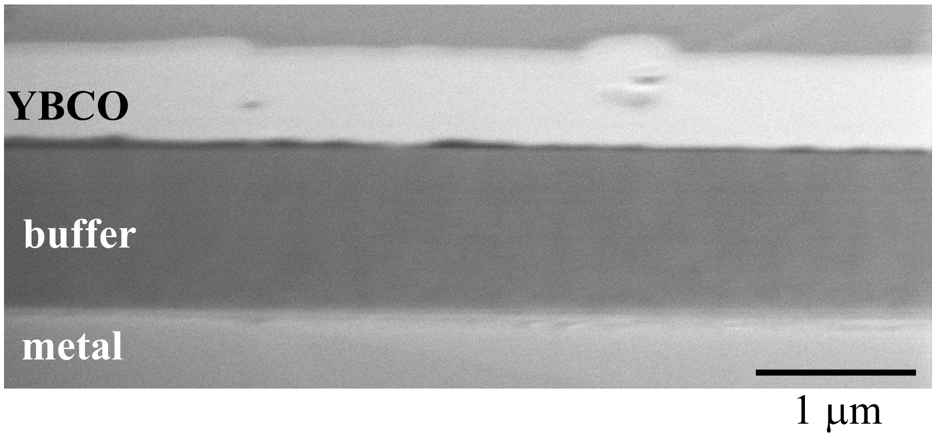


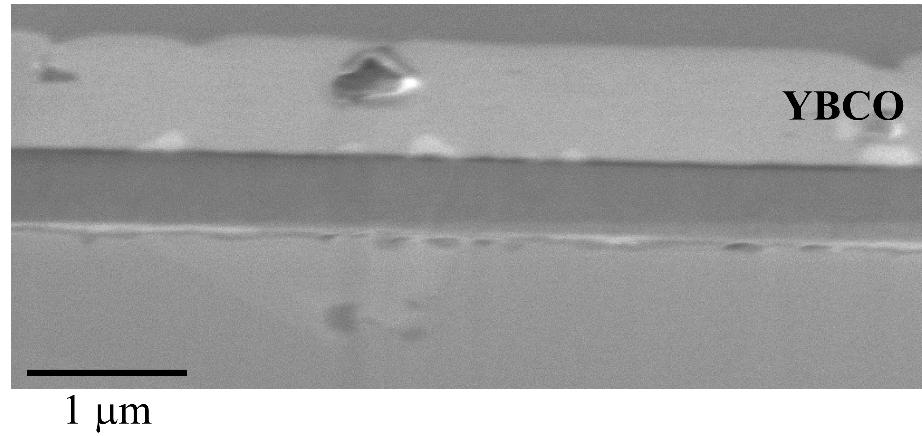
Deposition flux was centered



Improved ion beam profile uniformity

IBAD thickness reduced by 2.5x while maintaining high Ic





YBCO thickness = 0.9μm

I_c = 100A

J_c = 1.1MA/cm²

<u>Buffer thickness</u> = 1.5μm

YBCO thickness = 1.0μm

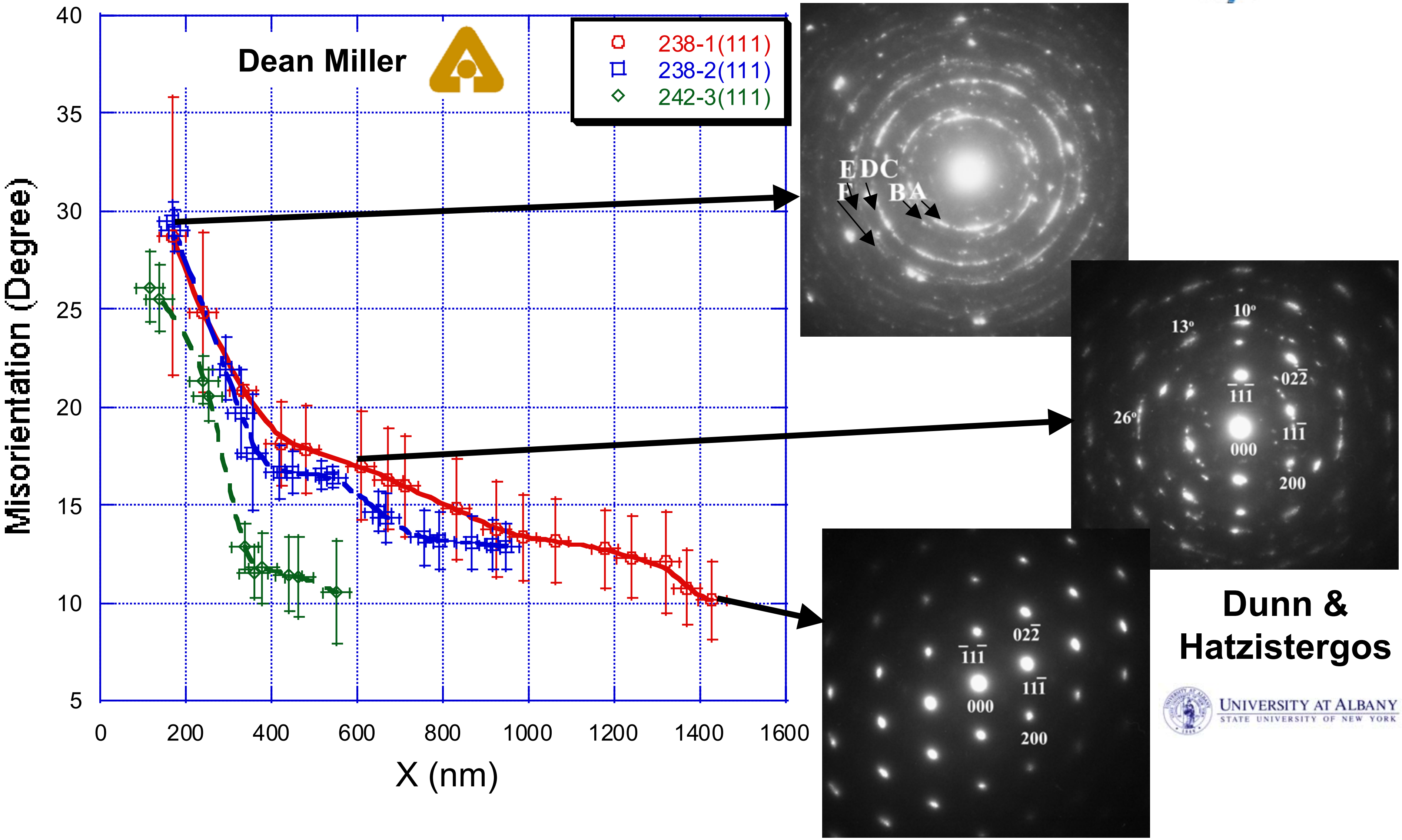
I_c = 132A

J_c = 1.3MA/cm²

<u>Buffer thickness</u> = 0.6μm

2.5x less buffer thickness enables 2.5x increase in throughput

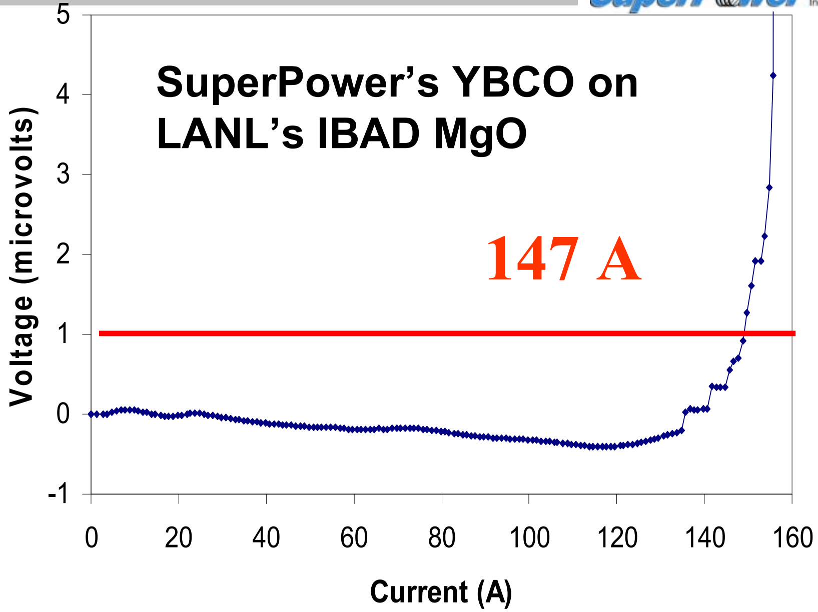
TEM study shows rapid texture evolution with new IBAD process conditions

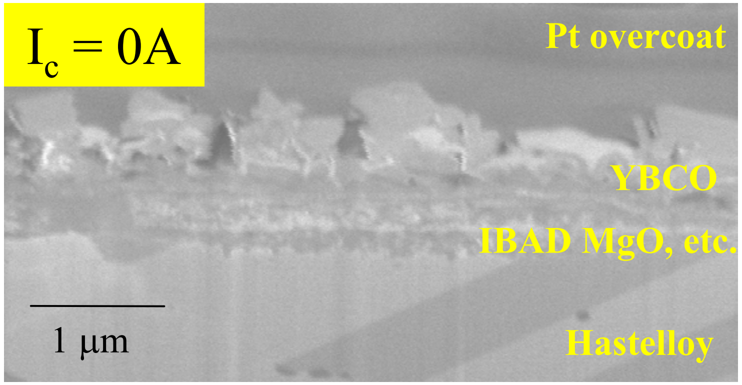


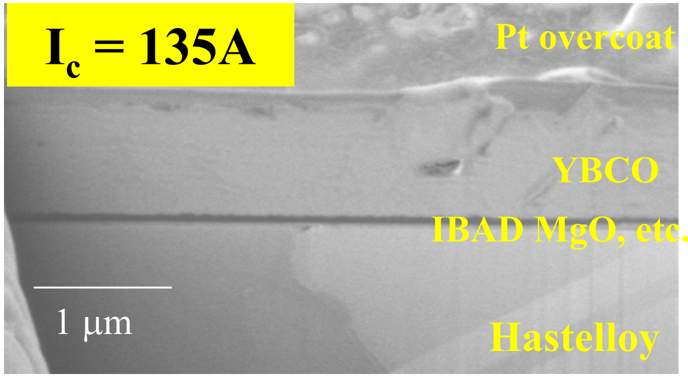
Parallel effort on transitioning to high-rate IBAD process has begun

<u>Our pathway to IBAD scale up</u> :

1. Develop hardware in our Pilot IBAD facility & address scale up issues with *<u>long runs & uniformity over large area deposition zone</u>* to produce 100 m tapes with *<u>proven</u>* IBAD materials.
2. In parallel, develop a high rate IBAD materials/processes.
3. Introduce the high-rate IBAD materials in our Pilot IBAD facility

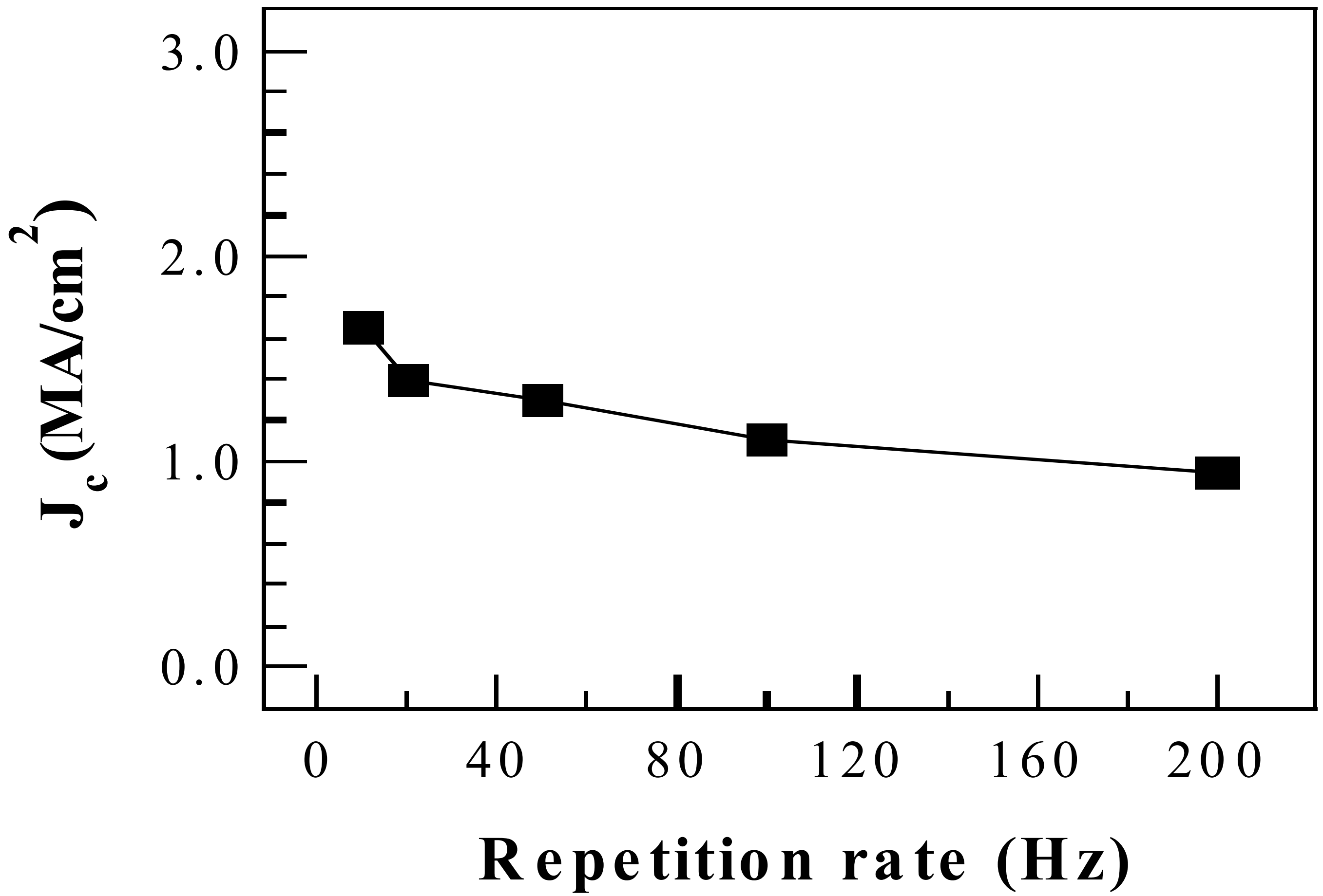




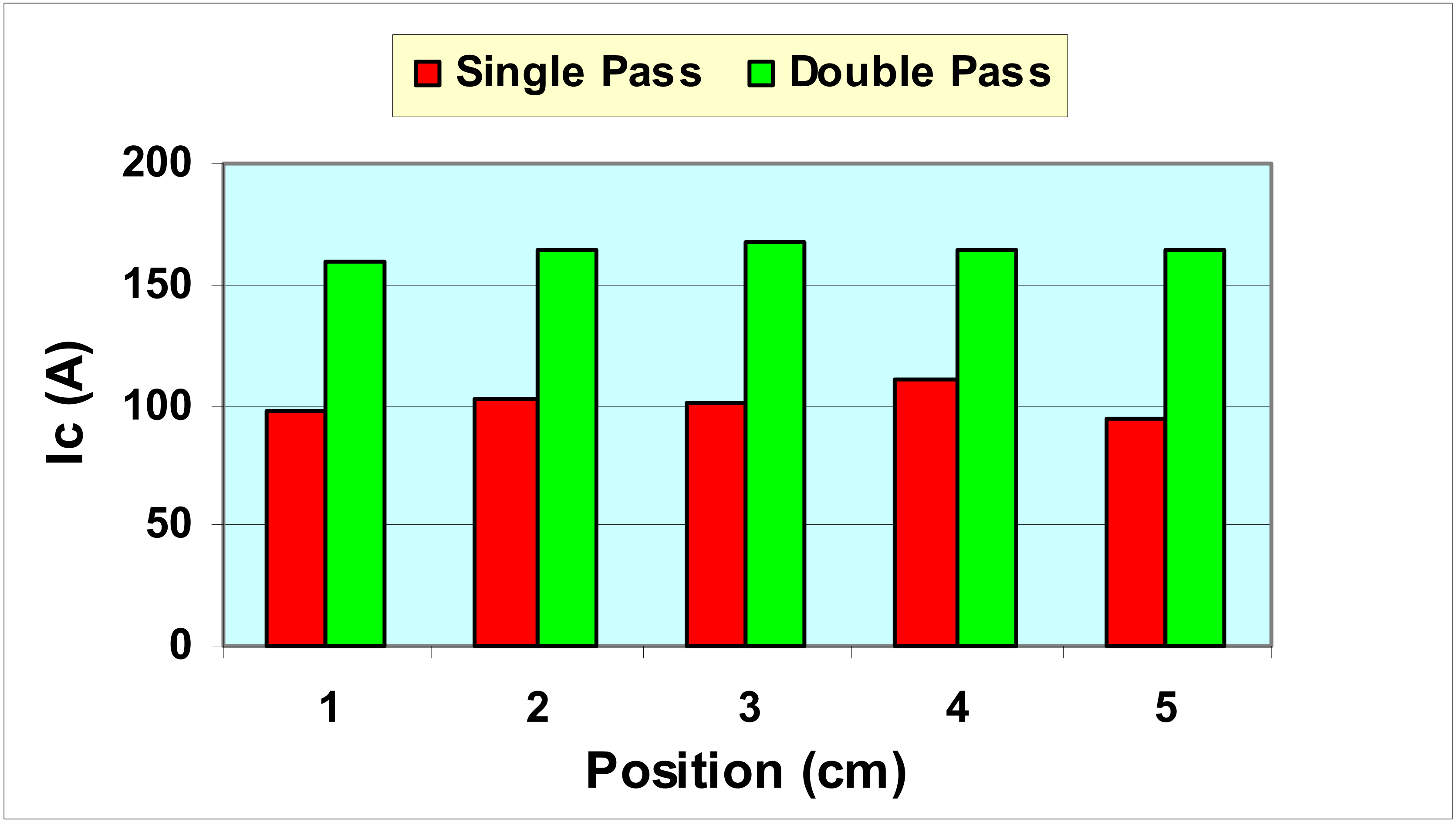


- Maximum J_c of 1.5 MA/cm^2 on 0.9 μm thick YBCO
- Data from seven runs show average I_c of 128A ± 14A.

High throughput with PLD : High Jc obtained at 200 Hz pulse repetition rate

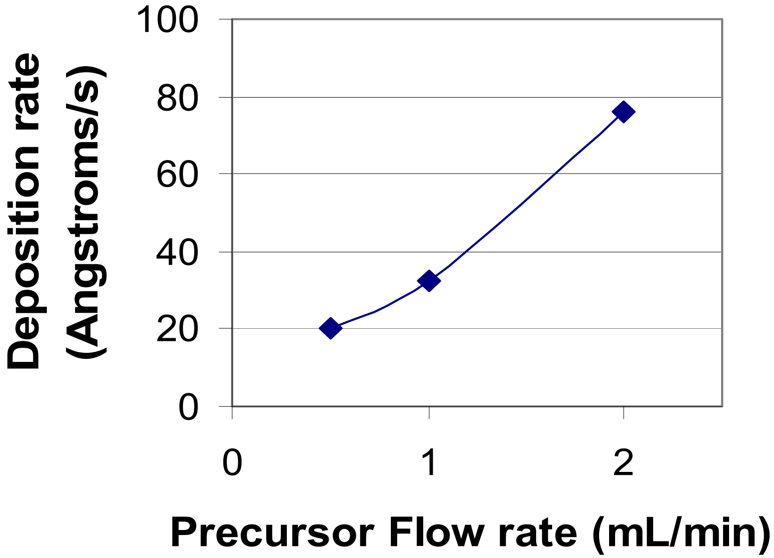


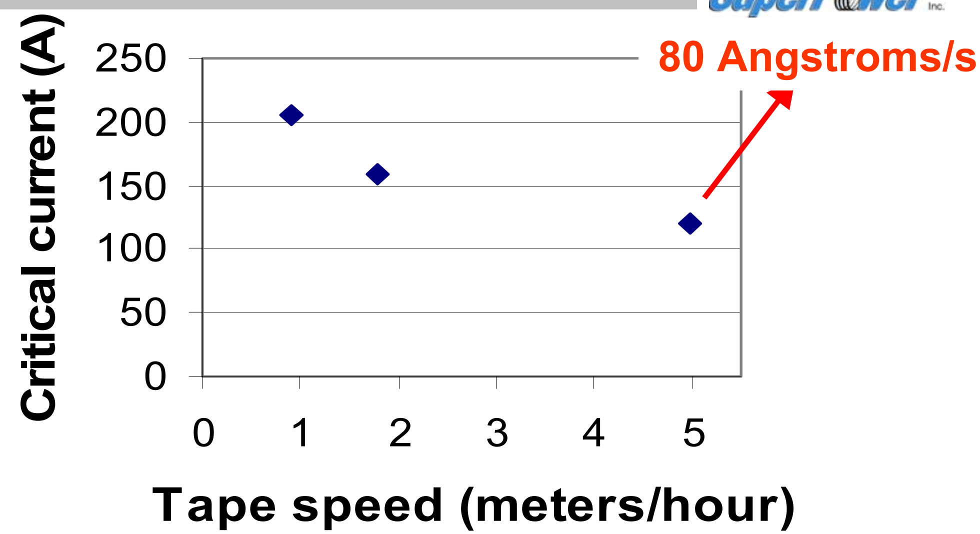
Increased throughput with PLD : Double pass enables reduced process cycle times

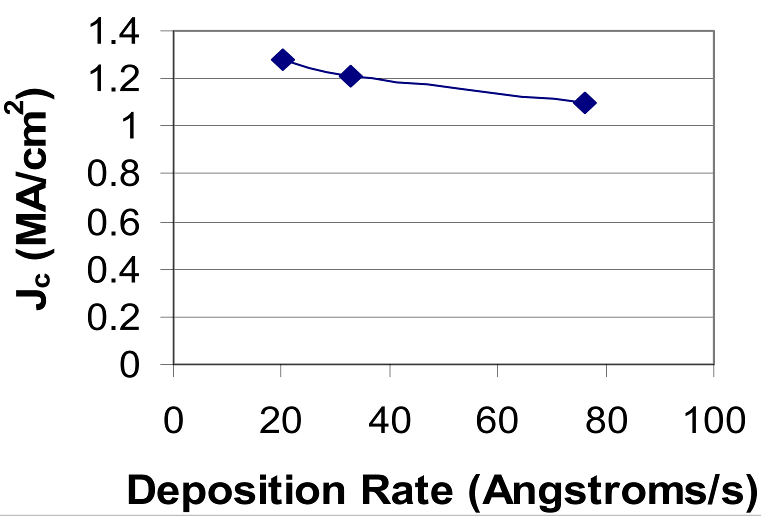


Reduced process cycle times preferred for process reliability, maintenance during long runs

5x throughput increase in MOCVD process







Deposition rate increased to 80 Angstroms/s just by increasing the precursor flow rate (no photo assist !). *More room for deposition rate increase by increasing flow rate further.*

Jc of 1.1 MA/cm^2 and Ic of 120 A achieved at a deposition rate of 80 Angstrom/second with MOCVD.

At 80 Angstrom/s & a deposition zone length of 20 cm in our MOCVD research tool, a tape speed of 5 m/h was used to produce 100 A tape

Alternate technique to produce longer lengths : Reduce Process cycle time

Short process cycle times not only desired to produce longer lengths & low-cost conductor, but also to increase the process reliability

Multiple Passes

First Pass: Deposit first *half* thickness of HTS layer

↓

Second Pass: Deposit second *half* thickness of HTS layer

↓

120A over 1 meter

No Ic degradation even when process cycle time is reduced to 1/2

Stop & restart

Shutdown the system during run (*on purpose*)

↓

Restart system & continue run

↓

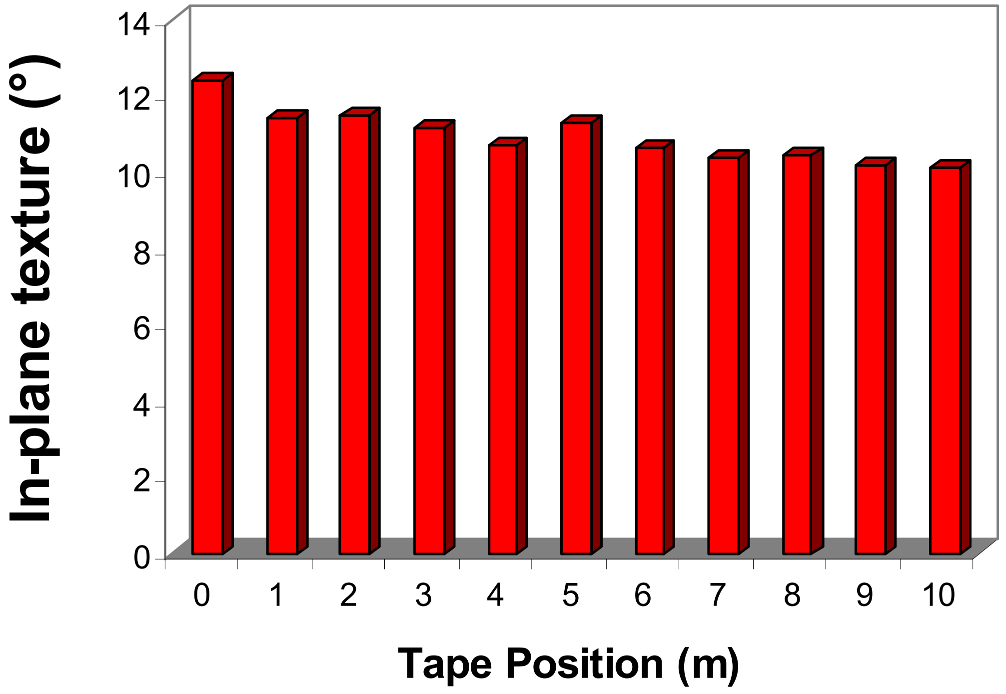
114A over 15cm

High Ic even if run is drastically interrupted!

Processing of longer lengths

Uniform, well-textured 10 m IBAD tapes produced

SuperPower Inc.

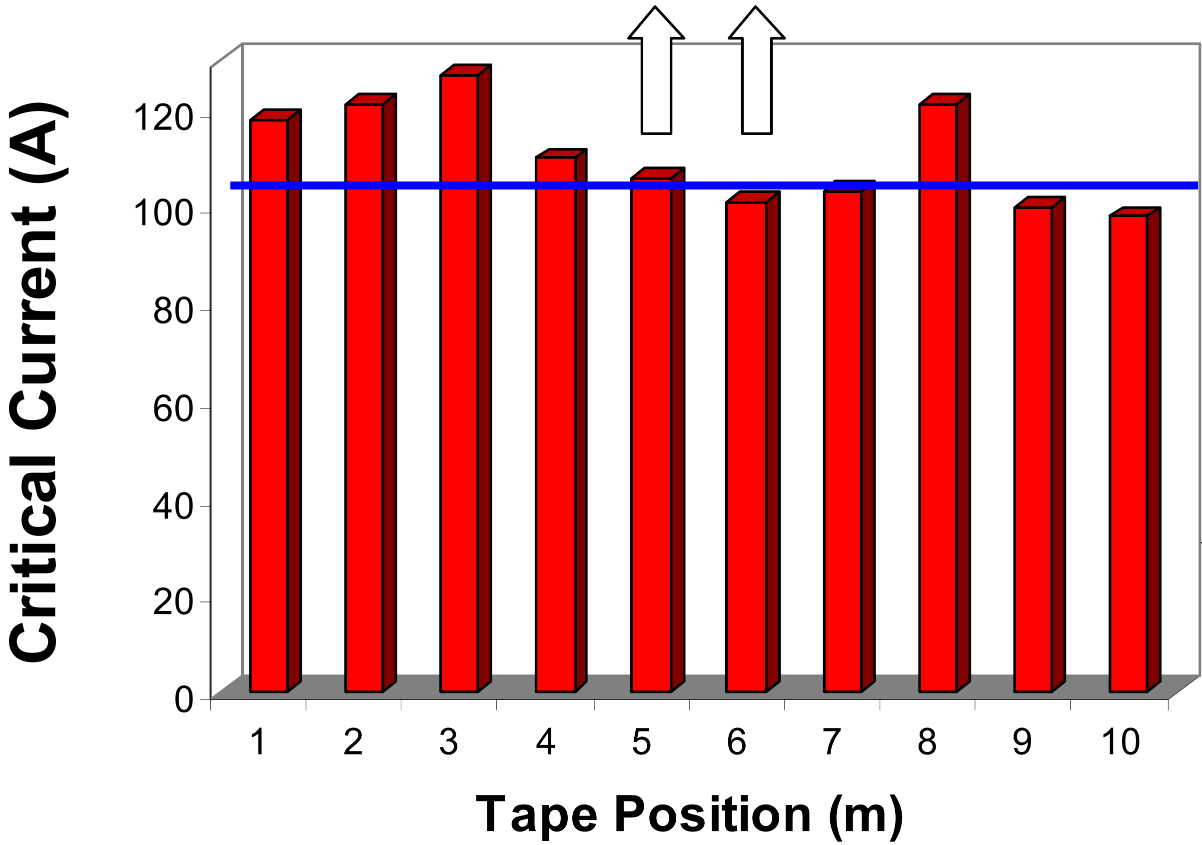


Average in-plane texture over 10 m = 10.9°

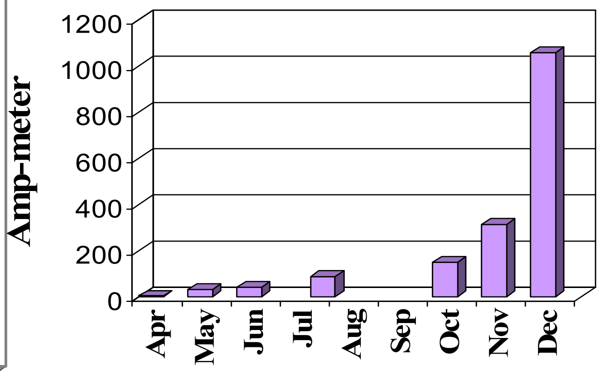
Standard deviation = 0.7°

We achieved 100+ A in our very first 10 m tape using PLD

SuperPower Inc.



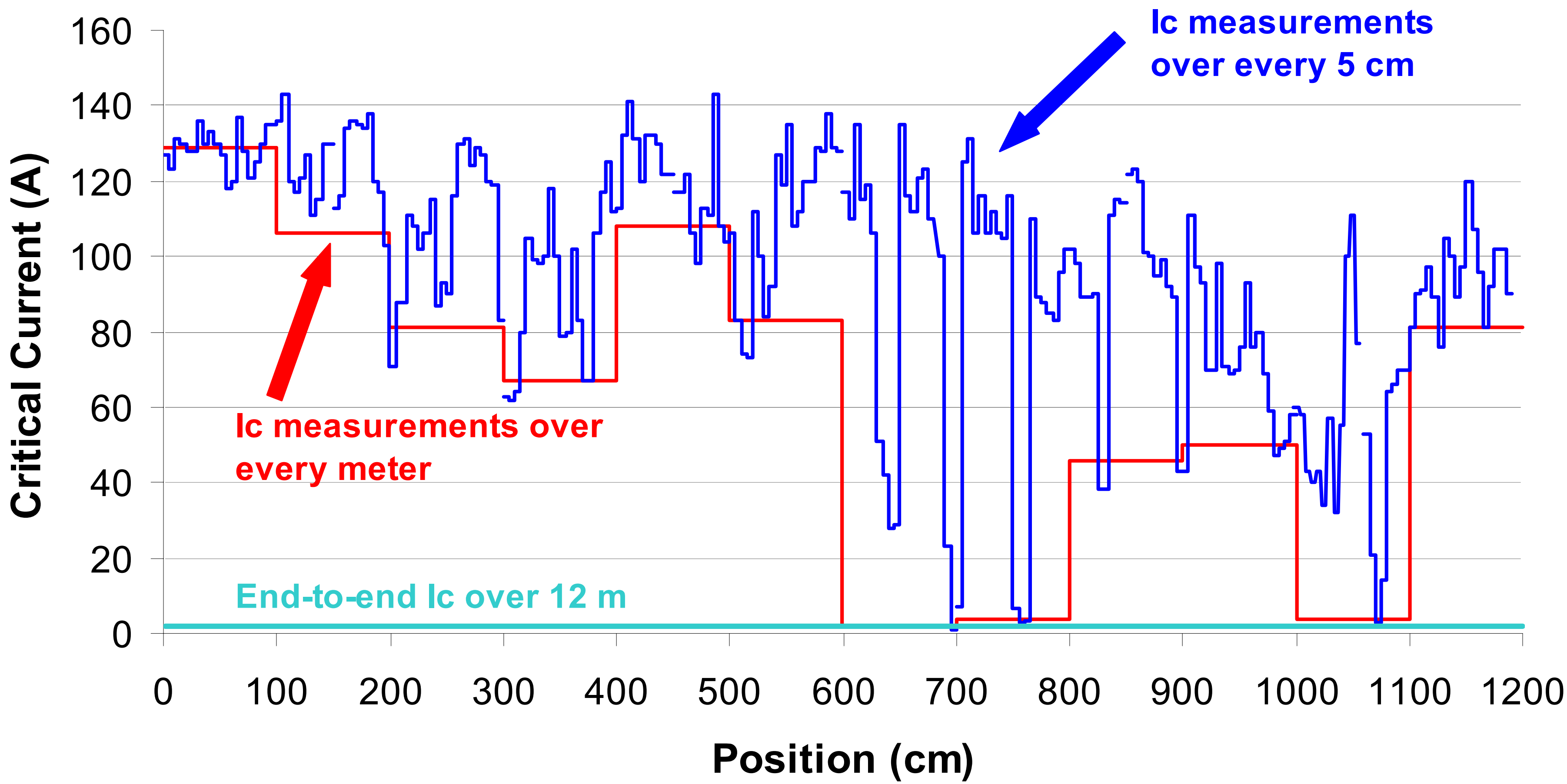
3 A-m to 1060 A-m in 8 months



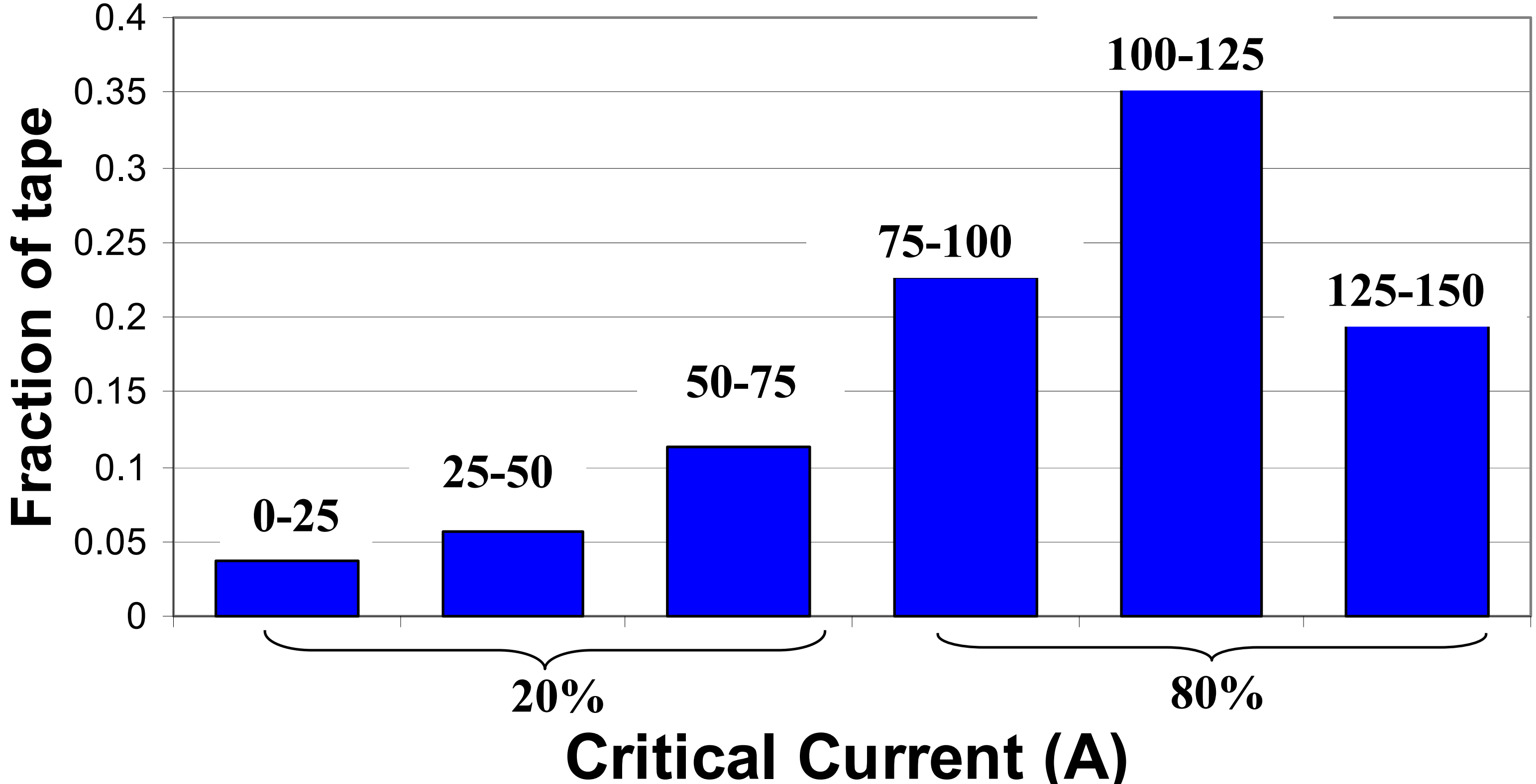
In Dec. 2002, 106 A over 10 m

I_c profiling by Reel-to-Reel I_c Rig enables detection of weak spots

SuperPower Inc.



A small percentage of weak spots responsible for low end-to-end Ic over 12 m



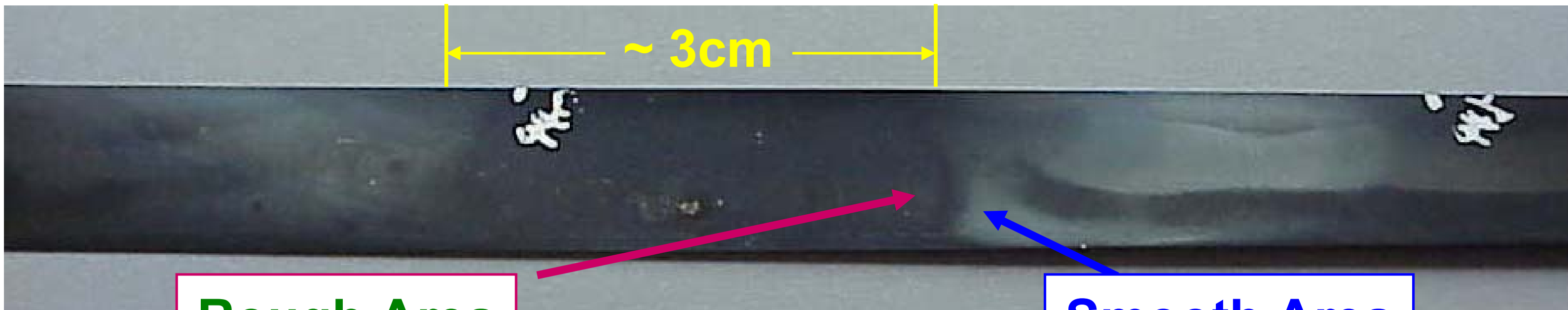
Average Ic over 12 m : 98 A

57% of tape has Ic > 100 A

91% of tape has Ic > 50 A

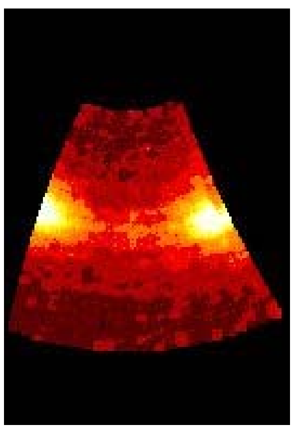
Identification of weak spots enables determination of root cause

755-760cm: 2.7 A

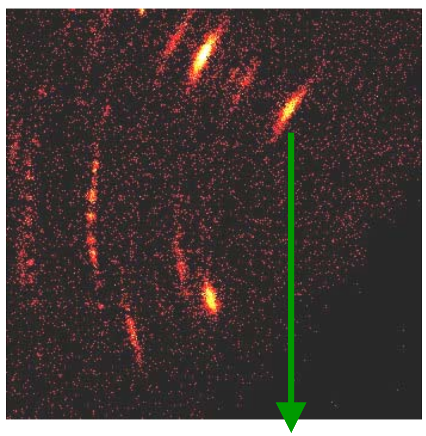


Rough Area

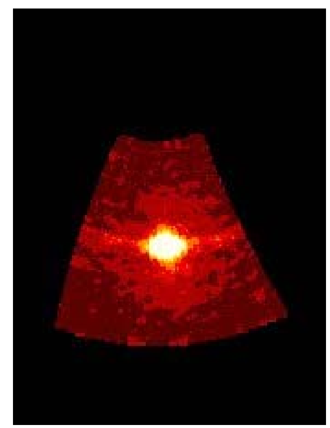
Smooth Area



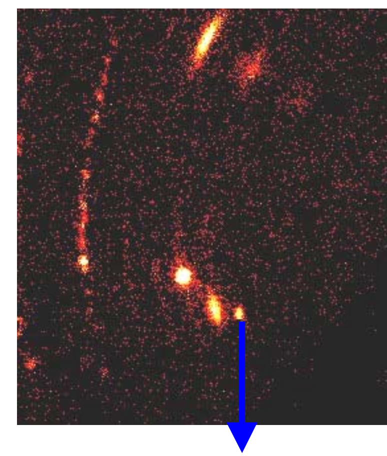
HTS with 2 orientations



CeO_2 layer misoriented

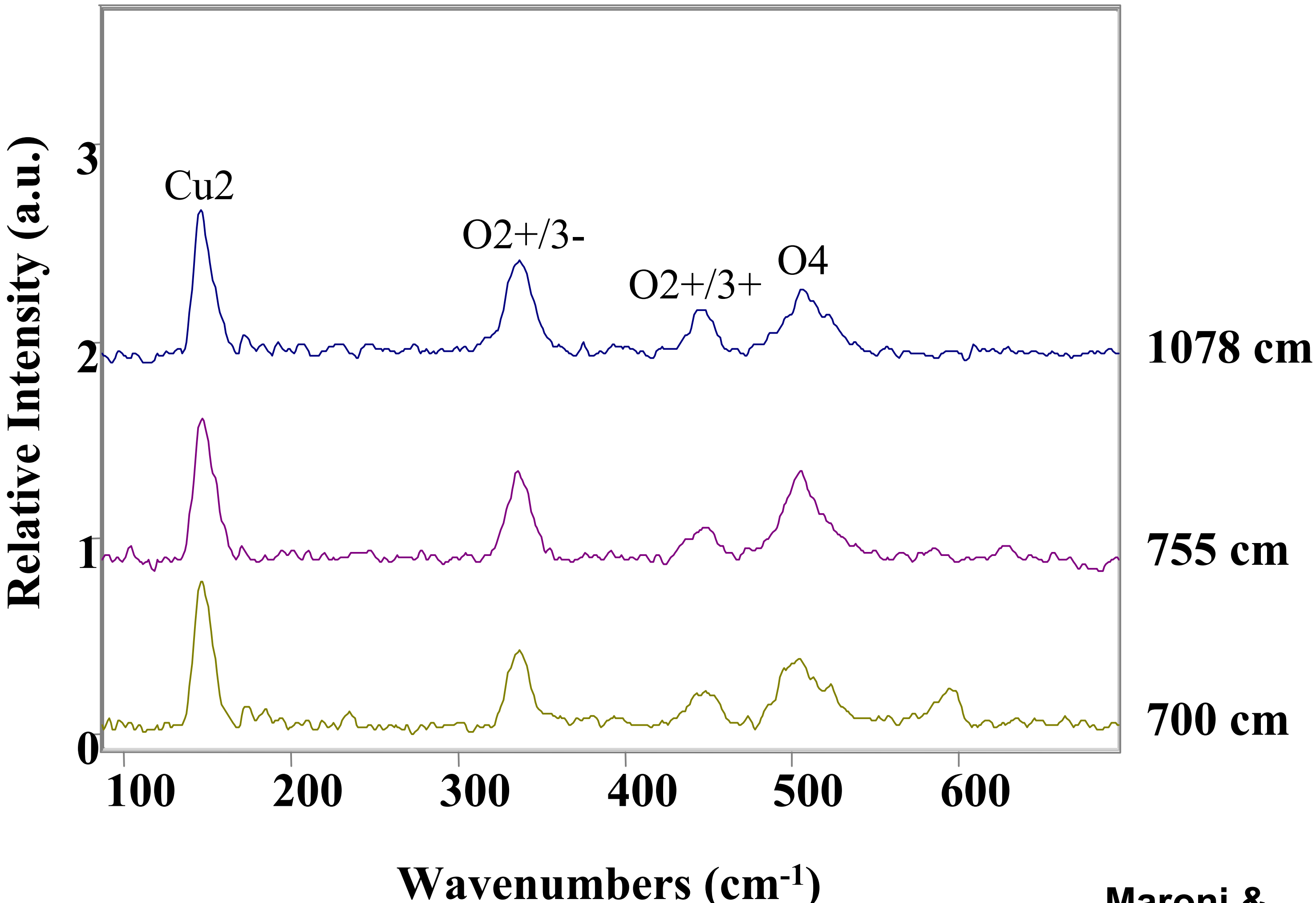


HTS with single orientation



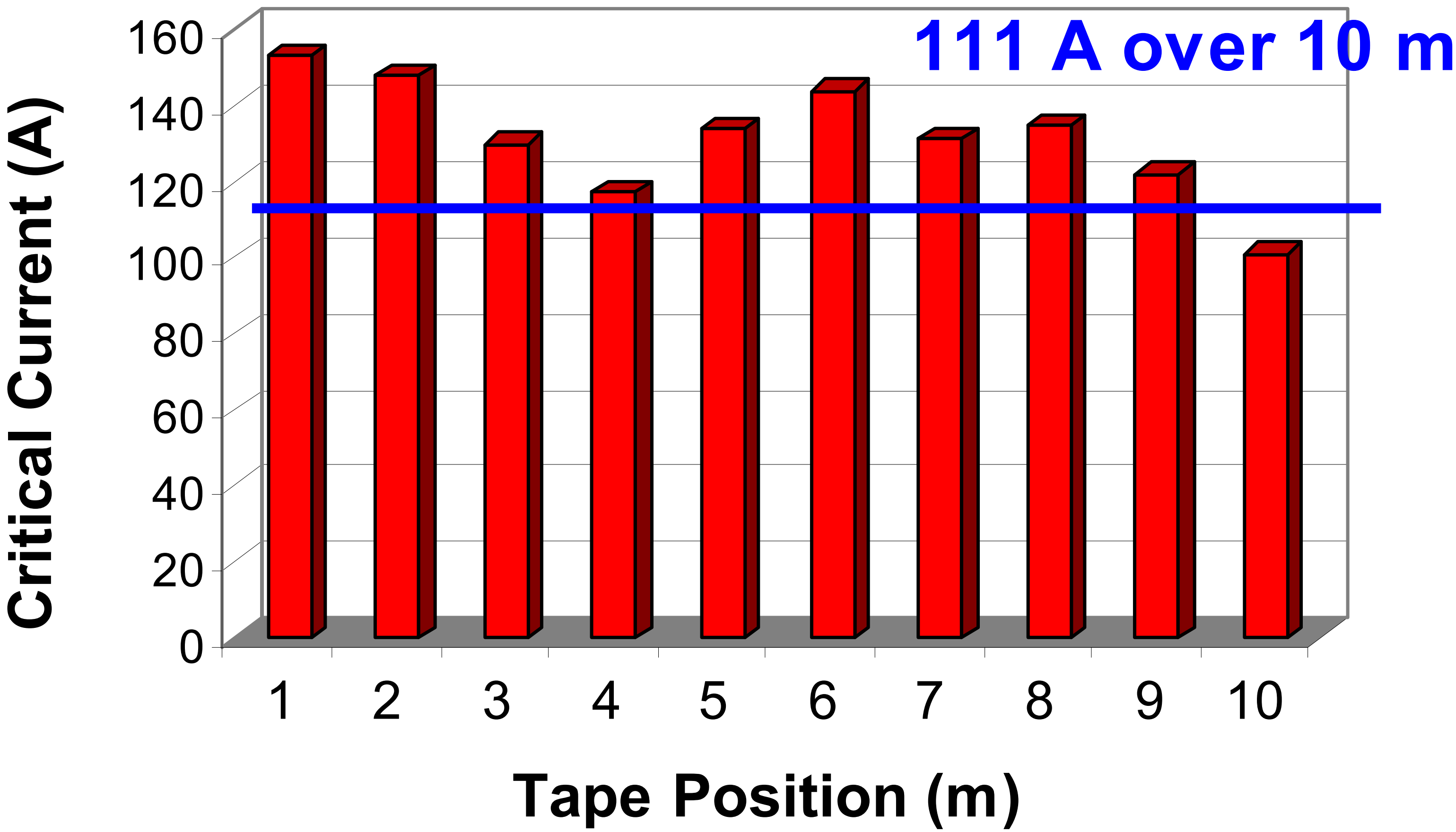
CeO_2 layer properly oriented

Raman in low I_c regions shows evidence of a-axis grains and poor oxygenation



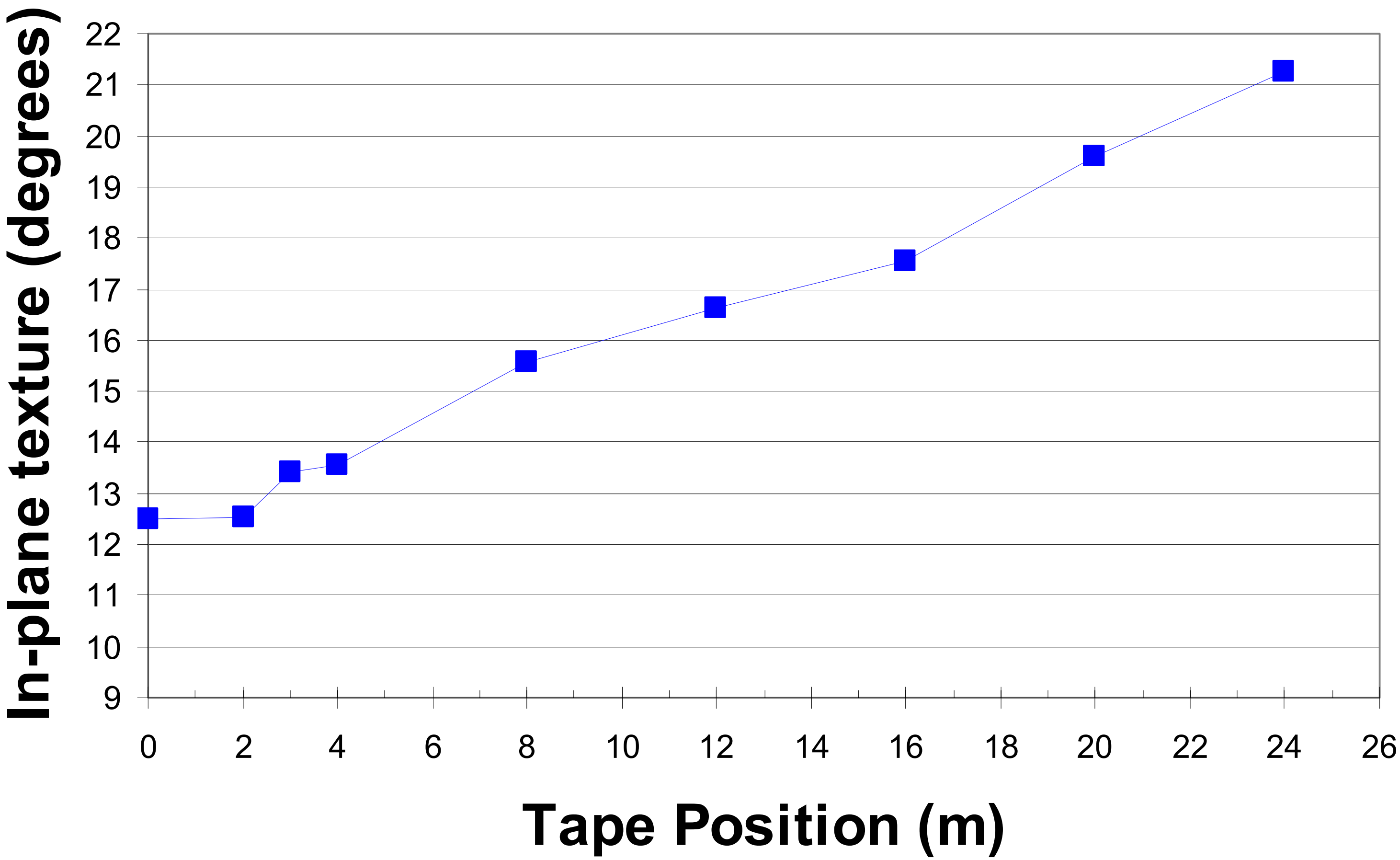
Maroni &
Venkatraman

Better control of MOCVD process yielded 100+ A performance over 10 m



Progress beyond 10 m lengths was difficult because of problems with texture uniformity with IBAD

SuperPower Inc.

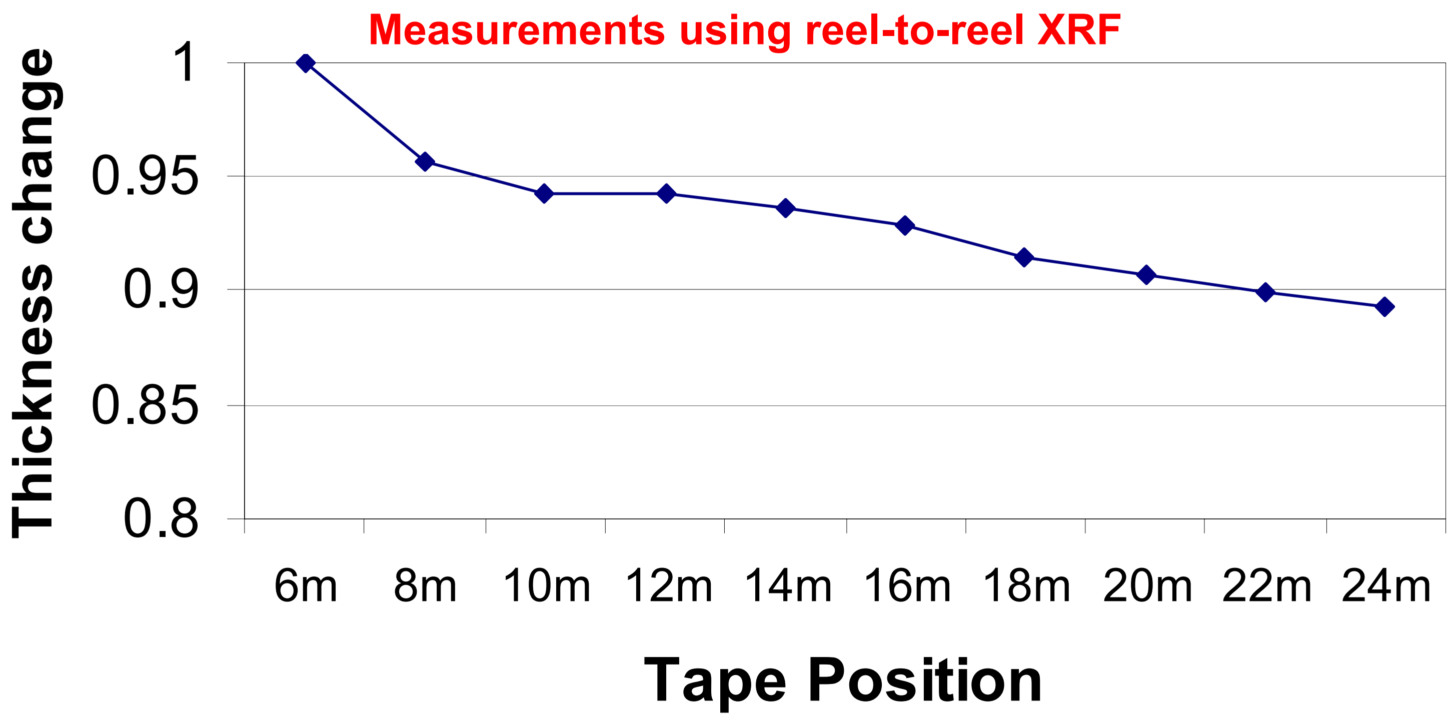


Early 20+ m IBAD runs with Helix tape handling system showed in texture degradation with length

Probable causes for texture degradation with length

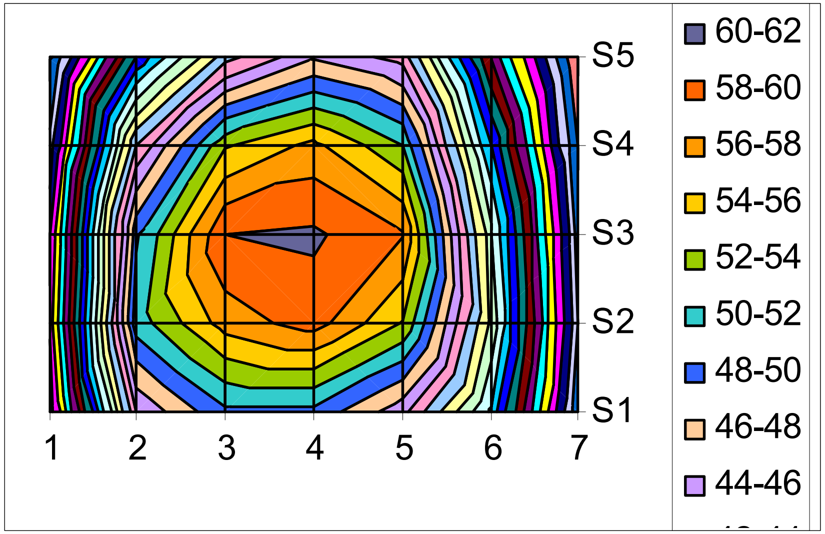
- **Temperature rise with time**
  - In the helix system, the tape stays in deposition zone 6 times longer than before.
- **Decrease in deposition rate with time**
  - Increased target curvature with time
  - Mechanical texturing of target surface with time
- **Ion beam profile changes with time.**
- **Contamination of chamber & target with time**

Possible cause for textured degradation :
Deposition rate decreases with time

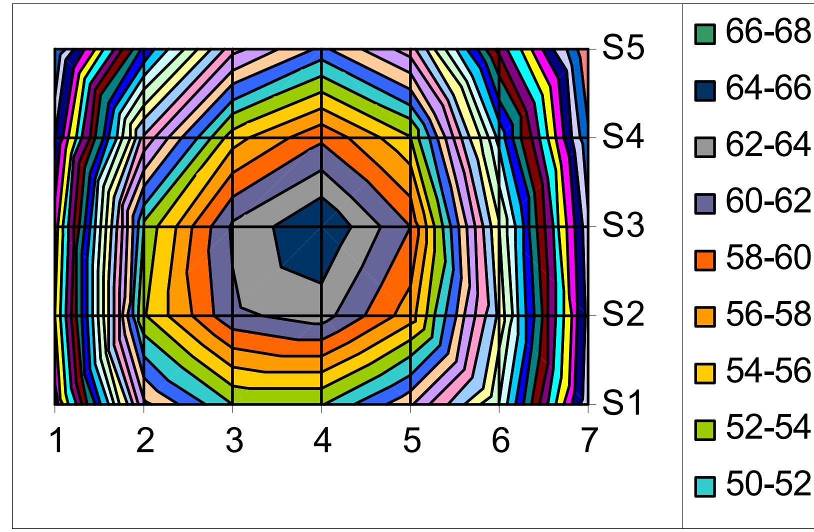


But, a 10% thickness change over 24 m can’t account for an in-plane texture increase from 12 to 21 degrees over that length

Possible cause for textured degradation :
Ion beam profile changes with deposition time



At beginning of run



At end of run

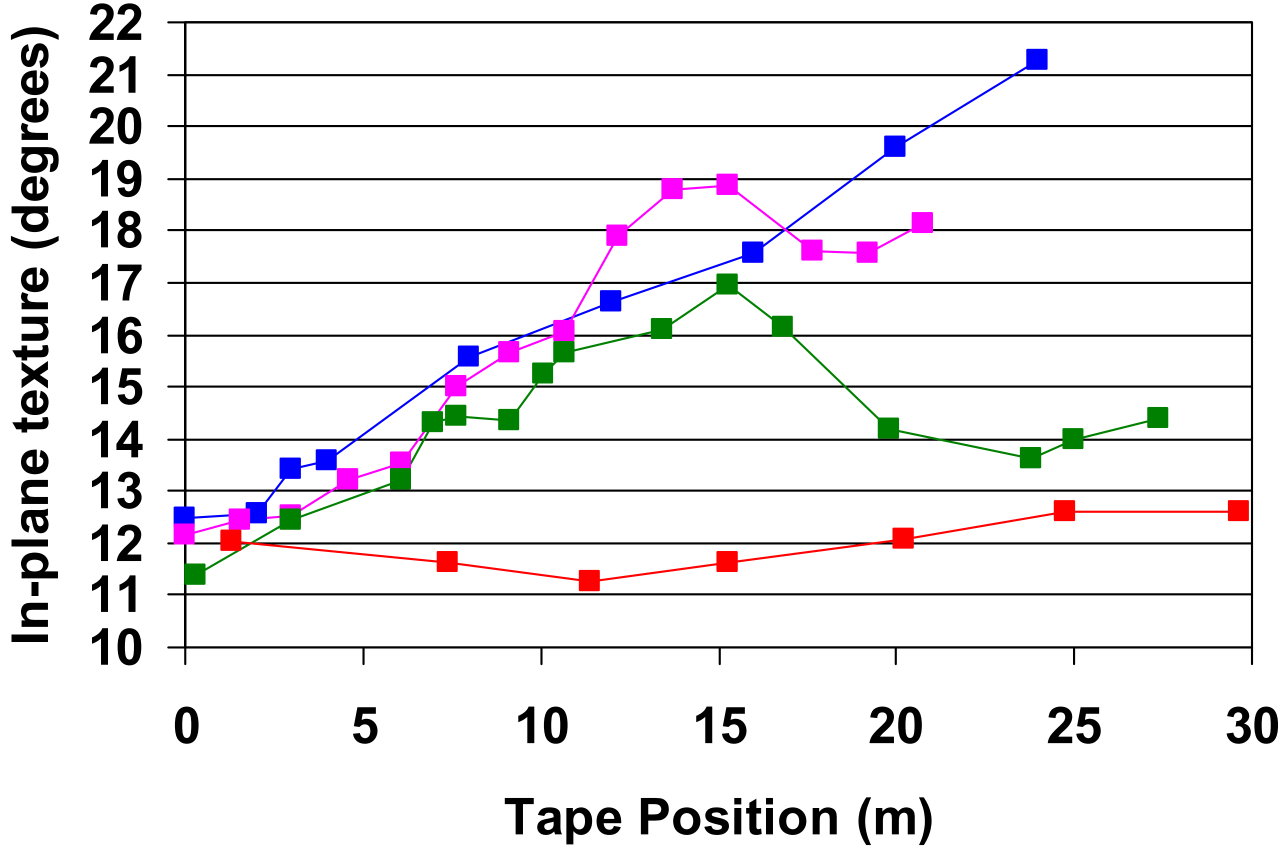
Possible Reasons for ion profile change :

Grid coated by deposit with time

Grid deformed due to temperature increase

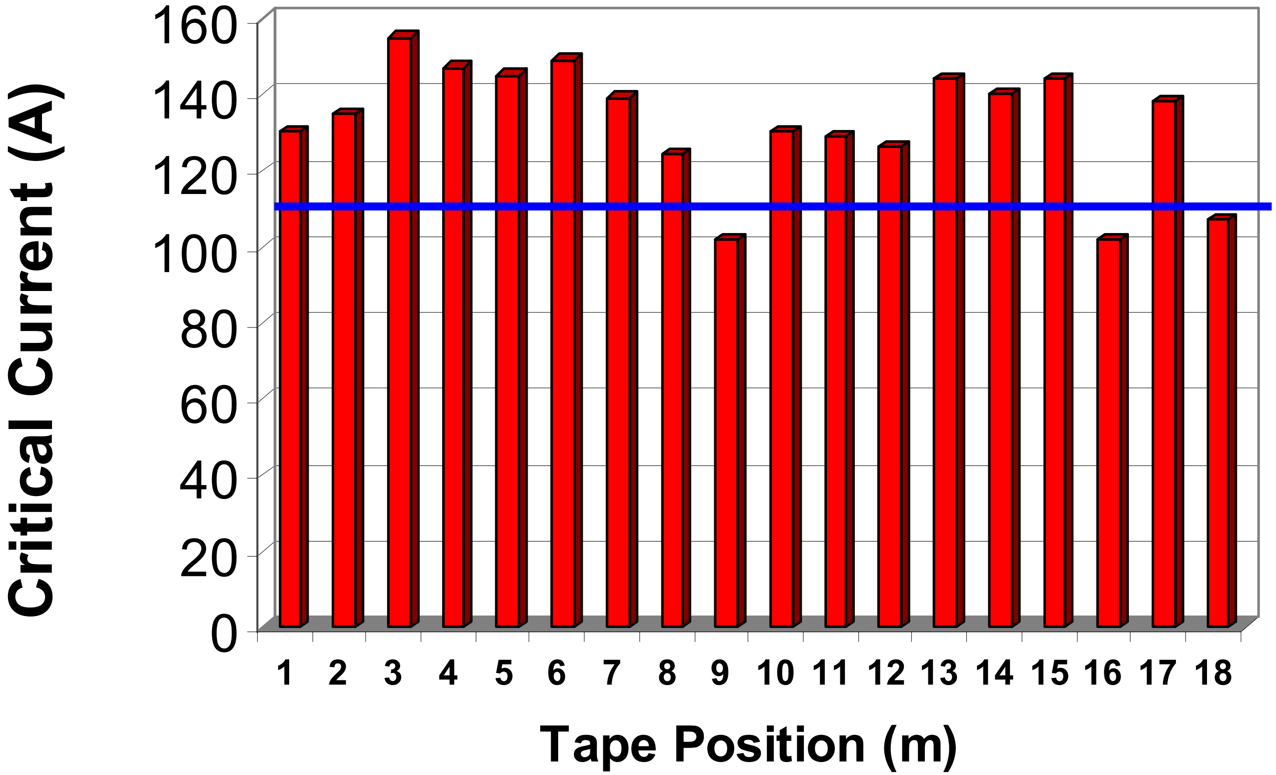
Insulation and conductivity of discharge chamber wall gradually changed due to plasma sputtering

Texture degradation avoided by optimizing the IBAD process & hardware



Achieved uniform in-plane texture of 12 degrees ± 0.7 degrees over 30 m

18 m long MOCVD tape with Ic > 100 A

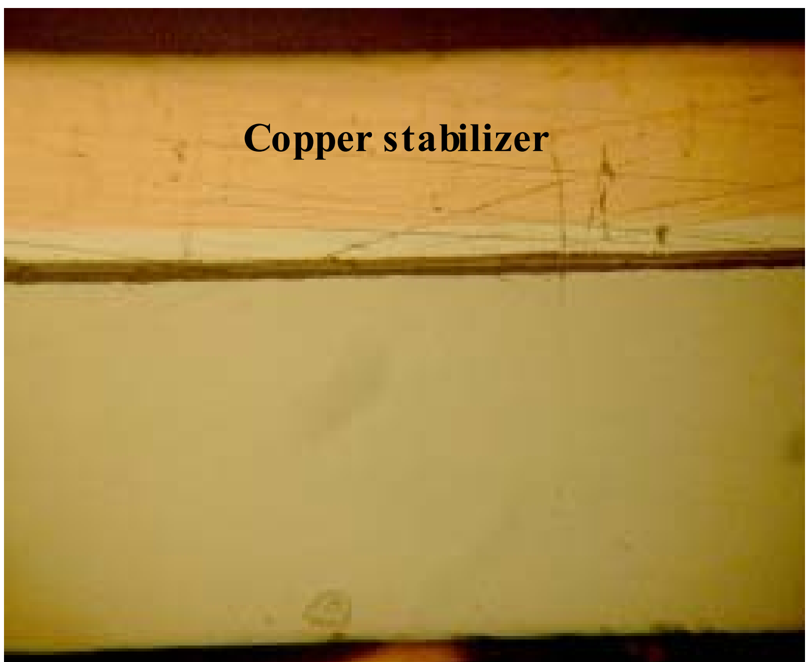


111 A over 18 m

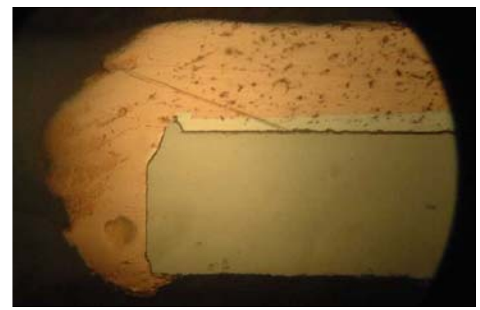
Practical Conductor Development

Electroplating demonstrated for copper stabilizer application on coated conductors

Tape including the substrate (melting point ~ 1400 C) can burnout at high currents !



- Thickness of the copper stabilizer can be well controlled by electroplating
- Operation close to room temperature - no molten metal used

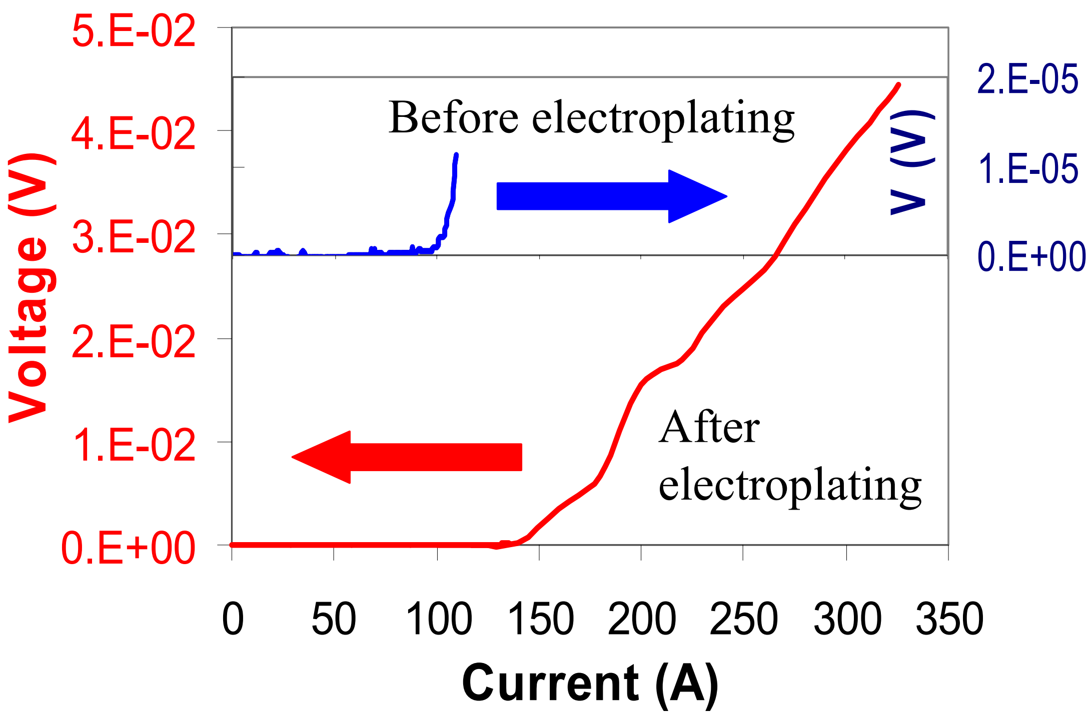


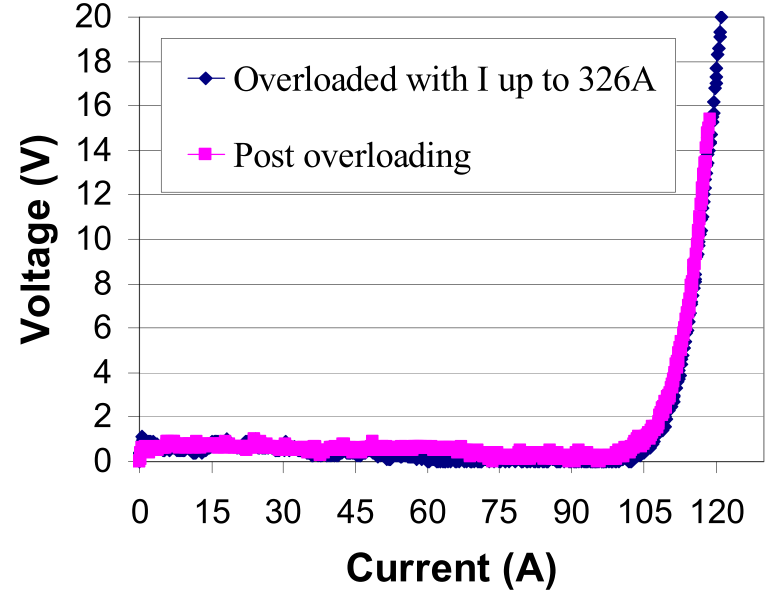
- Electroplating rounds off sharp edges

  can be important for reducing partial discharges at high voltages that the HTS electric power devices will operate at.

- Double sided coatings and complete side wall coverage in a single pass

Electroplating demonstrated as a viable technique for copper stabilizer application





No loss in critical current after electroplating copper stabilizer.

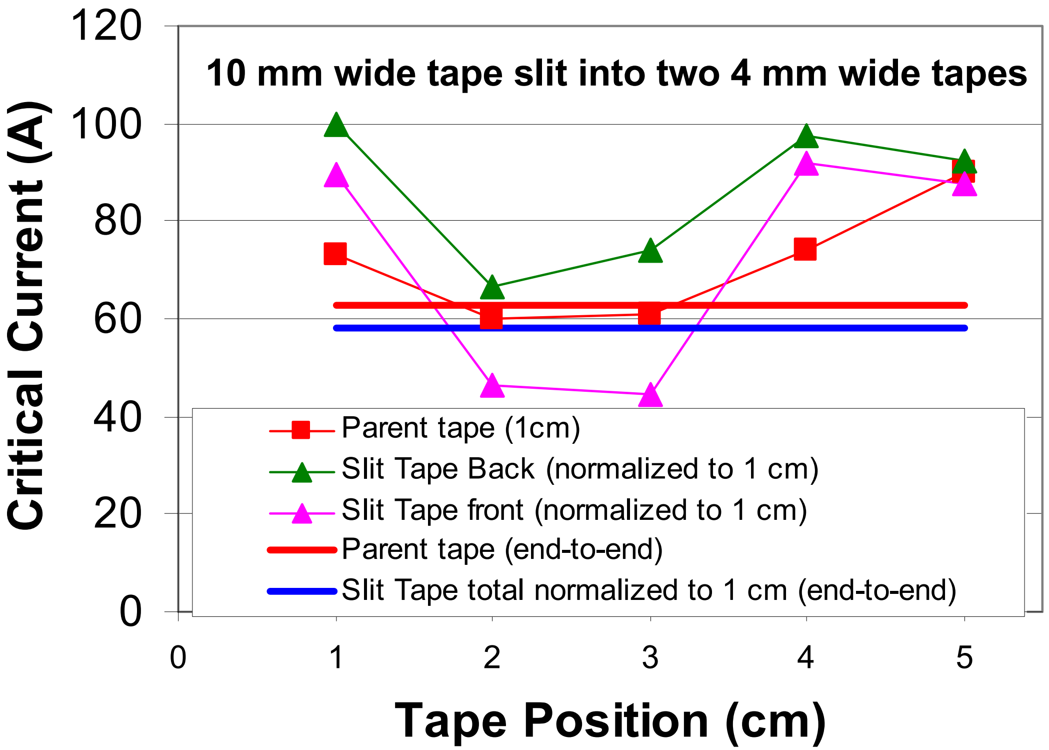
Electroplated tape overloaded to three times Ic (326 A) & 1000 times higher voltage

No change in critical current when retested after overloading to 326 A

Slitting of fully-processed coated conductor tapes

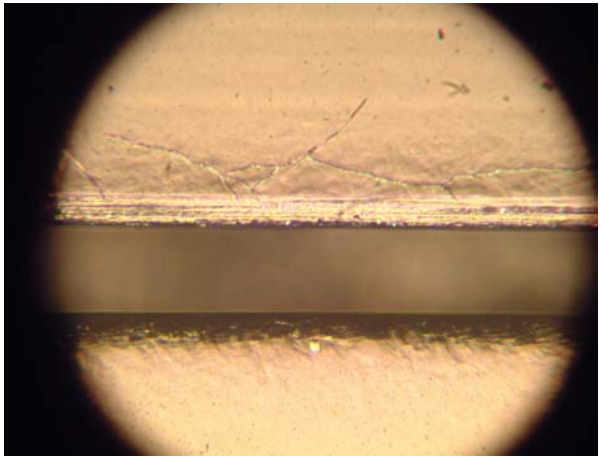
4 mm wide tapes are need for cable applications

- start with 4 mm wide tapes : slitting not needed ; but processing can be complex
- start with a wider tape and slit to multiple 4 mm wide tapes : more efficient, but risk of losing Ic during slitting

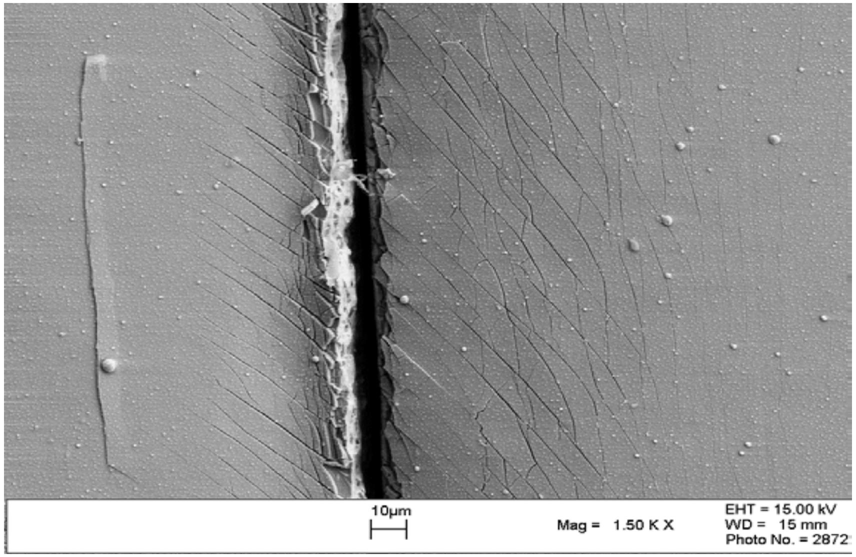


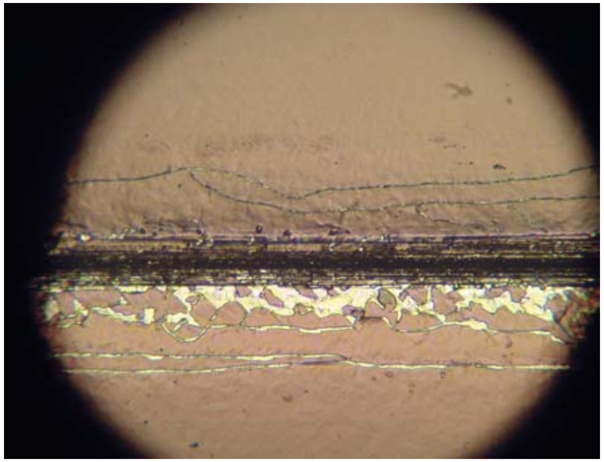
8% decrease in end-to-end Ic after slitting
Ic of the two 4 mm tapes are different !

Control of crack propagation important to reduce loss in Ic after slitting

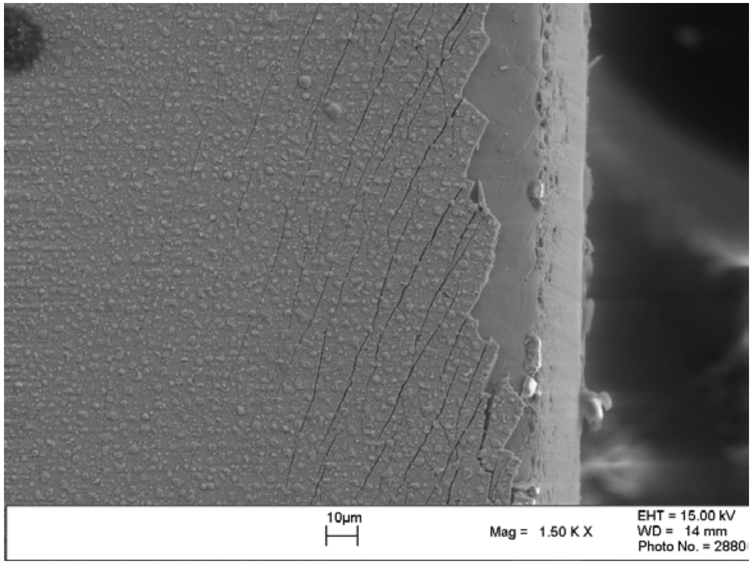


Good slit edge

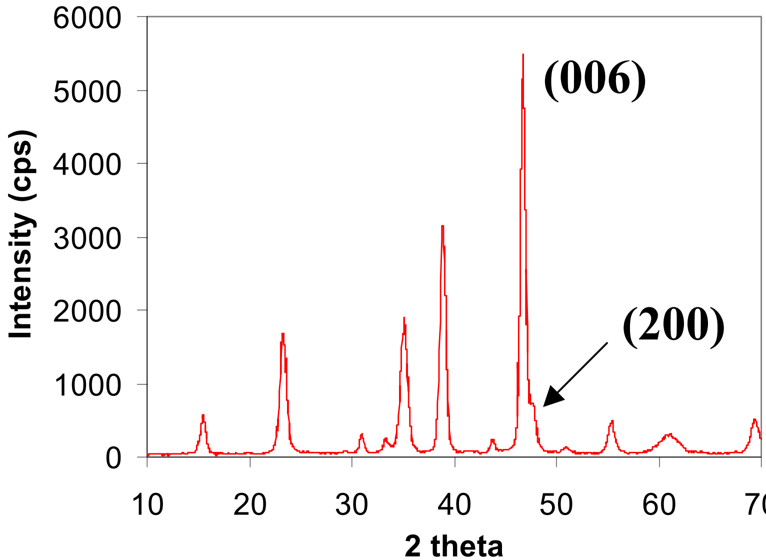




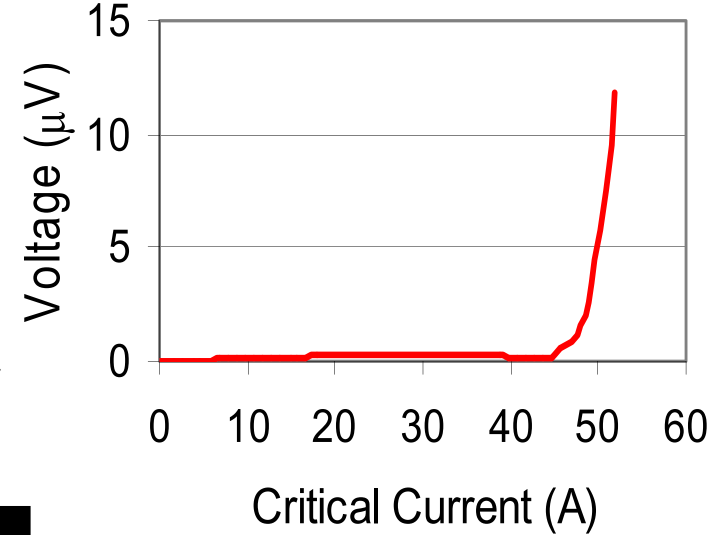
Slit edge with defects

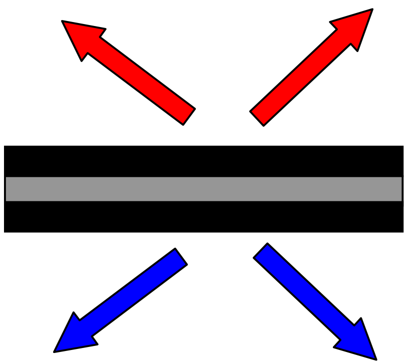


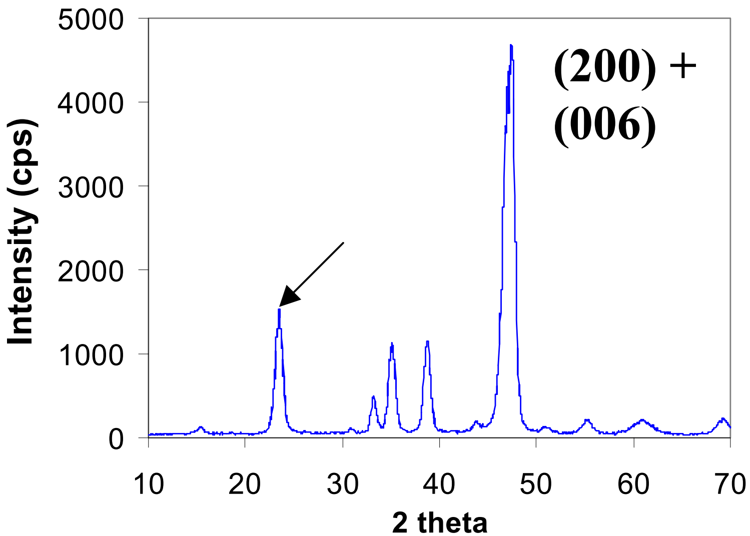
Nonuniformity of parent tape quality across width can lead to Ic differences in the slit tapes



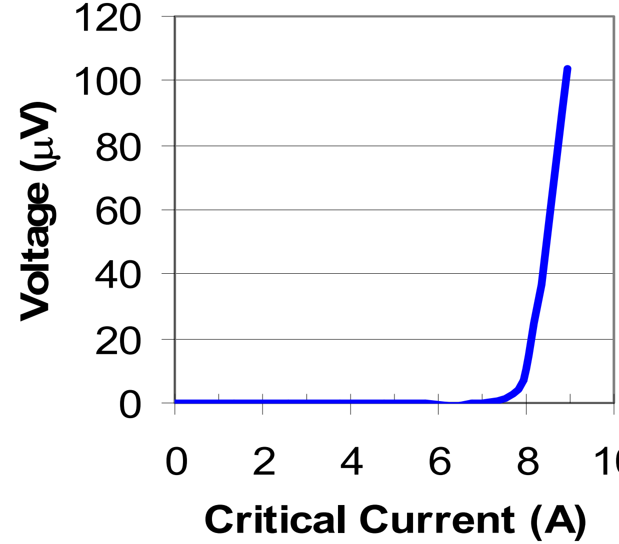
Back of tape
Good texture
Ic = 150 A/cm





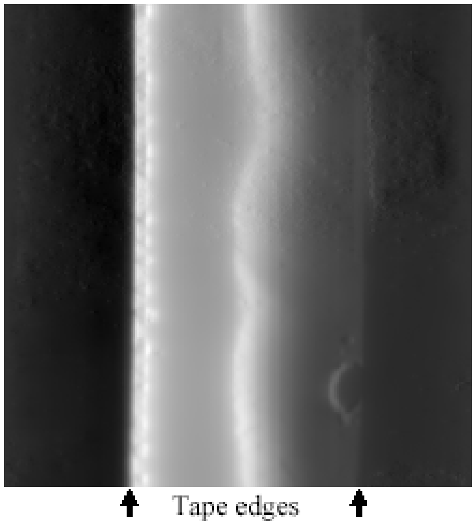


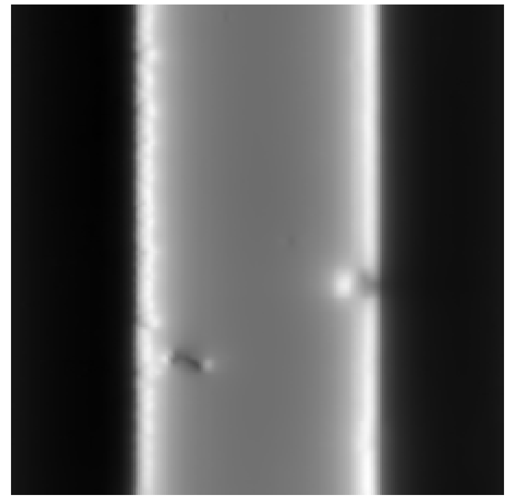
Front of tape
Poor texture
Ic = 20 A/cm

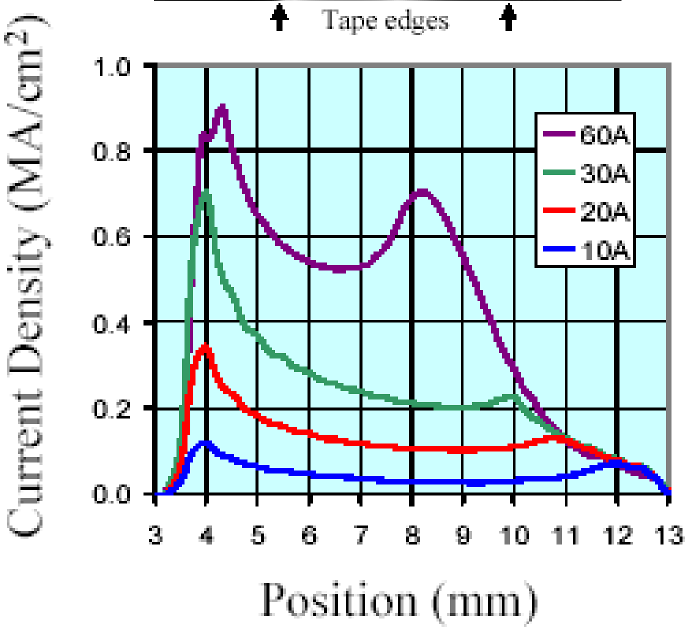


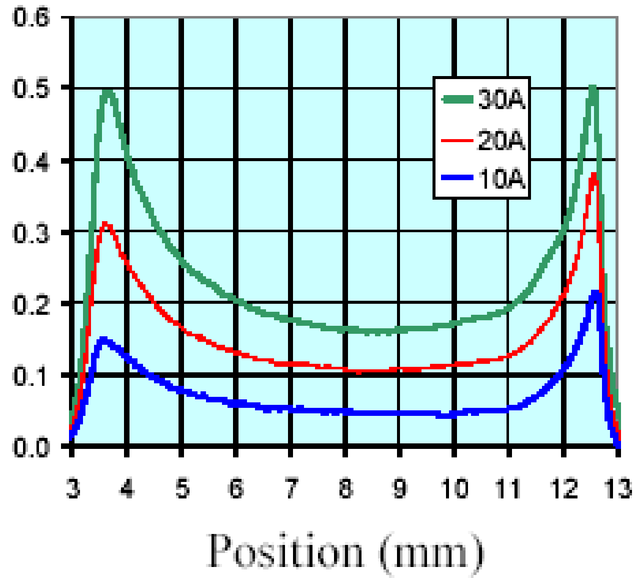
Magnetic Imaging used as a non destructive method to qualify nonuniformity of parent tape prior to slitting process

SuperPower Inc.









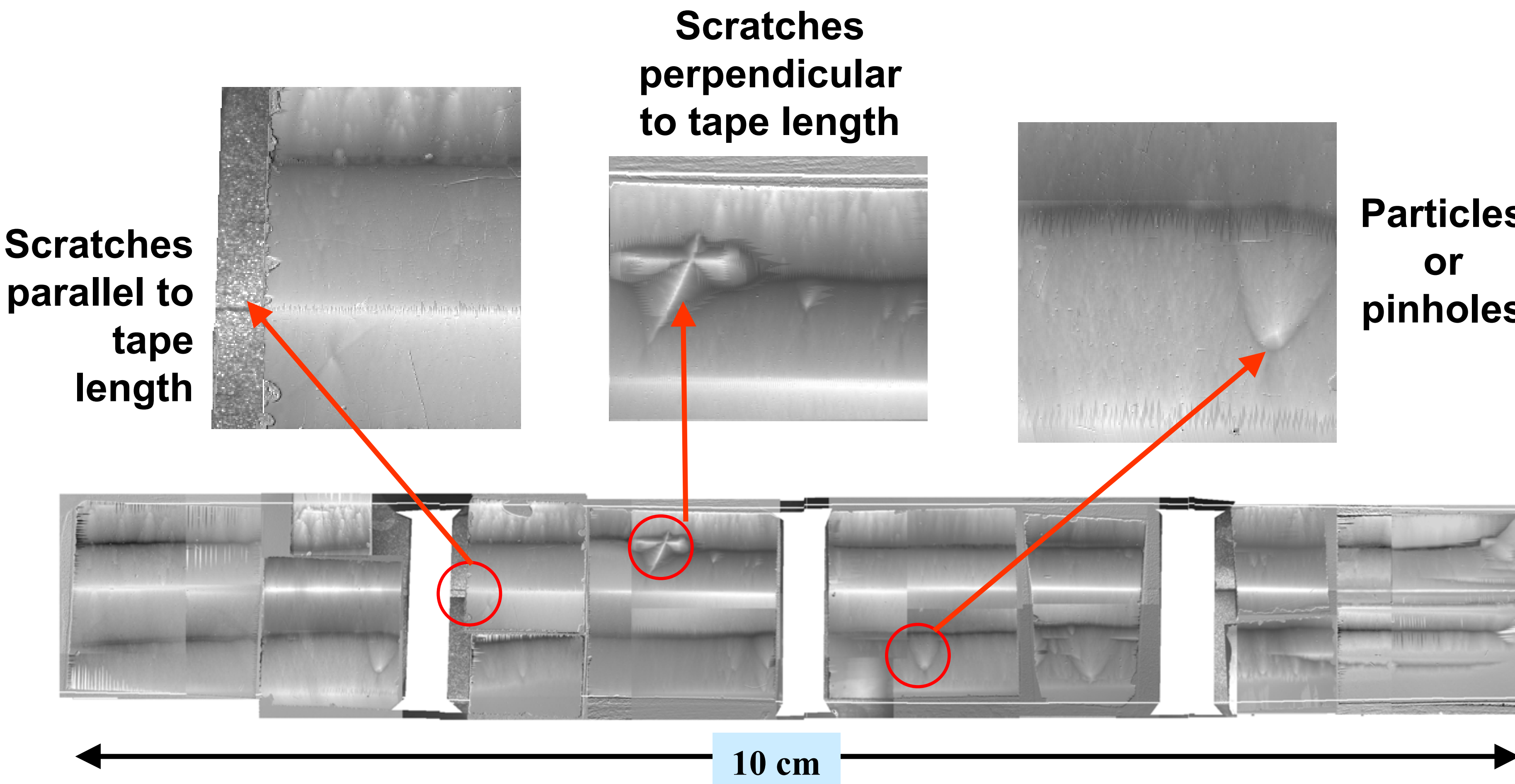
<u>Need</u> : To examine Ic variation across tape width non destructively.

<u>Purpose</u> : Examine current flow before & after slitting to differentiate between non uniformity in Ic of parent tape & damage caused by slitting

Measurements by Fred Mueller

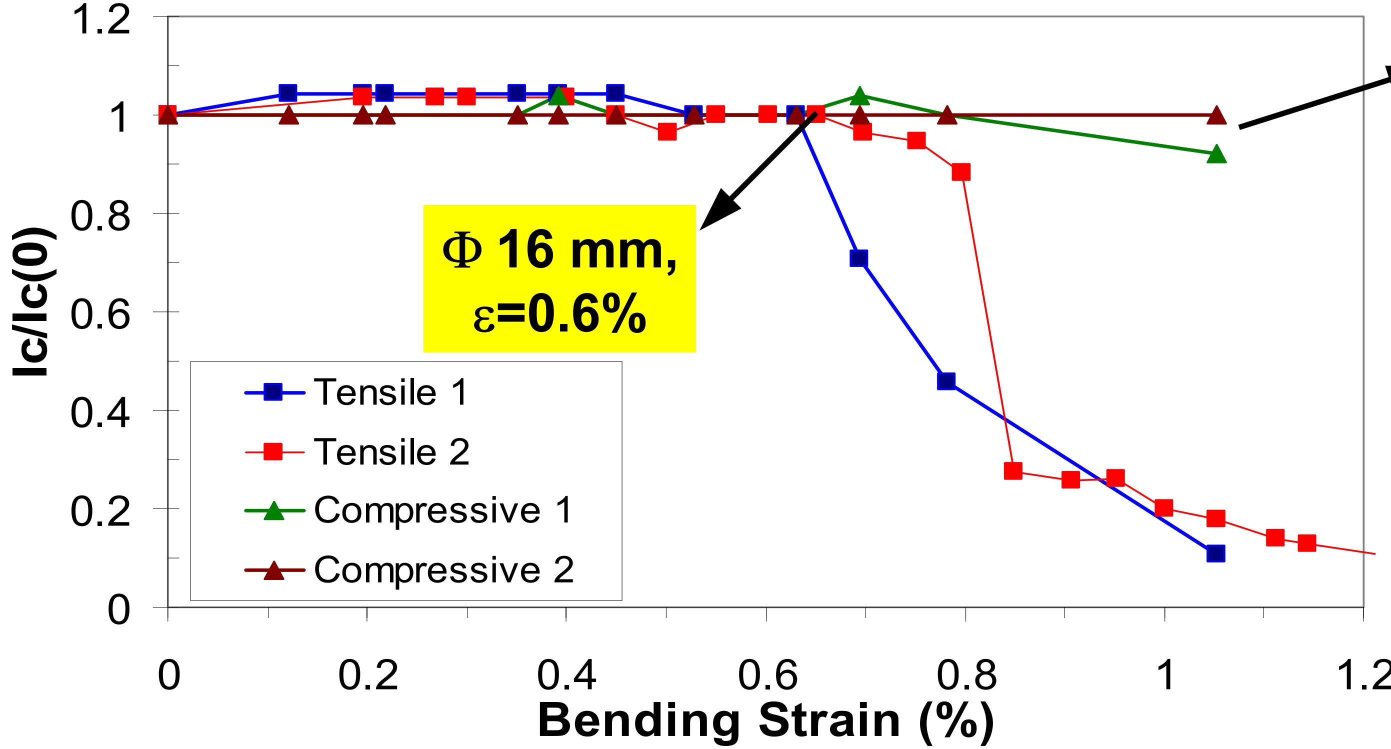
1943 - 2003 Los Alamos NATIONAL LABORATORY

Magneto-optical imaging can also be used to qualify nonuniformity prior to slitting



Ken Gray

Bending tests on our *unreinforced* tapes show good Ic retainage



Total tape thickness = 107 microns ; HTS thickness = 0.7 - 0.9 microns

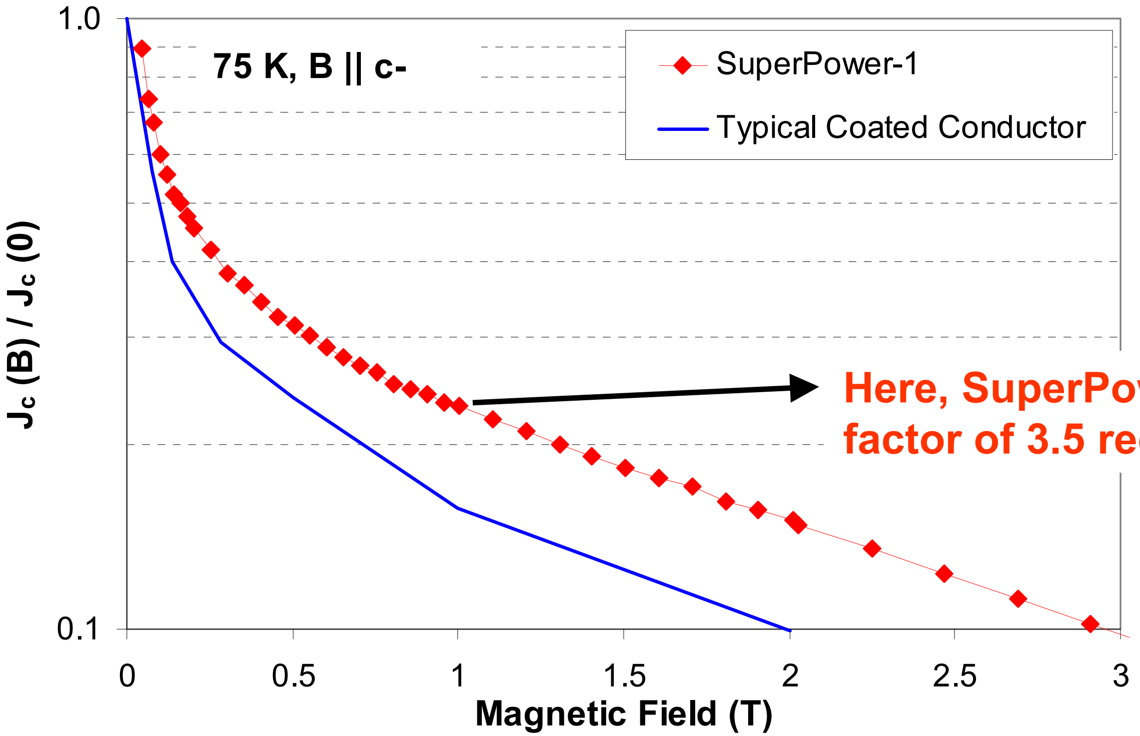
Silver overlayer thickness = 5 microns ; *No copper stabilizer*

HTS layer is 9 times farther away from the neutral axis that it is to the tape surface, but still 100% of critical current retained even when subjected to 0.6% tensile strain, or wound around 16 mm dia mandrel.

To Achieve 100 A @ 1 T : Development of a Coated Conductor with Better Magnetic Field Performance

Jc of typical coated conductor with Jc ~ 1 MA/cm^2 at zero field, reduces by a factor of 7 to 10 at 1 T.

Starting with a 100 A conductor, the Ic at 1 T would then be only 10 - 15 A



Measurements by Leonardo Civale

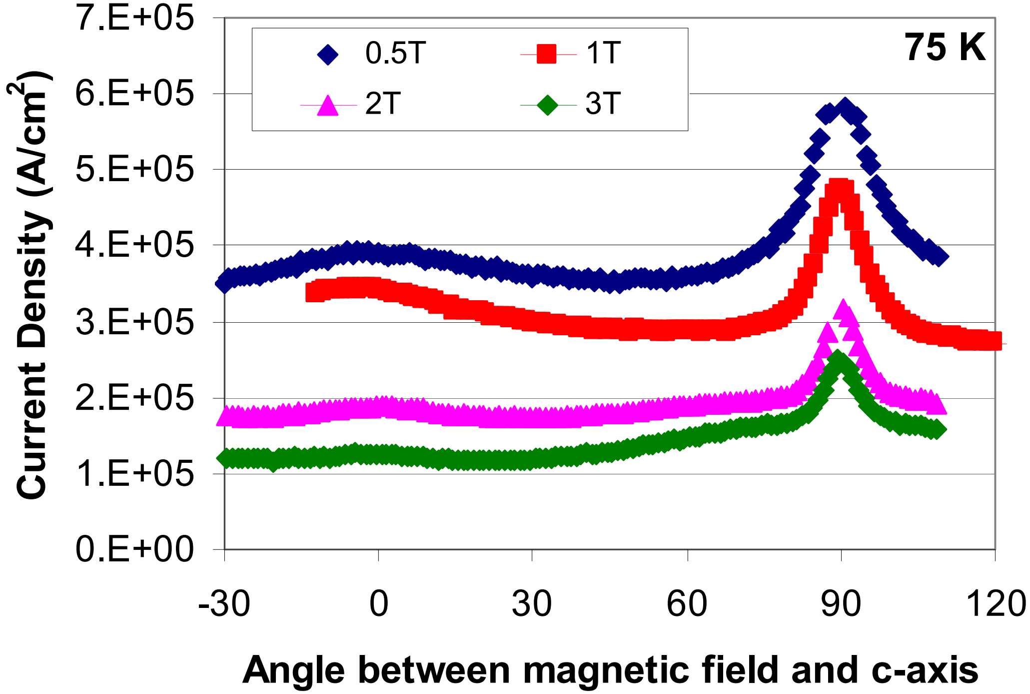
1943 - 2003 Los Alamos NATIONAL LABORATORY

Here, SuperPower tape shows only a factor of 3.5 reduction in Jc at 1 T.

All SuperPower tapes have shown reduction of less than a factor of 4 at 1 T
This is 2 times better performance in field than a typical coated conductor

SuperPower tapes show superior field dependence not only at B || c, but even intermediate field orientations

SuperPower Inc.



Measurements by Leonardo Civale

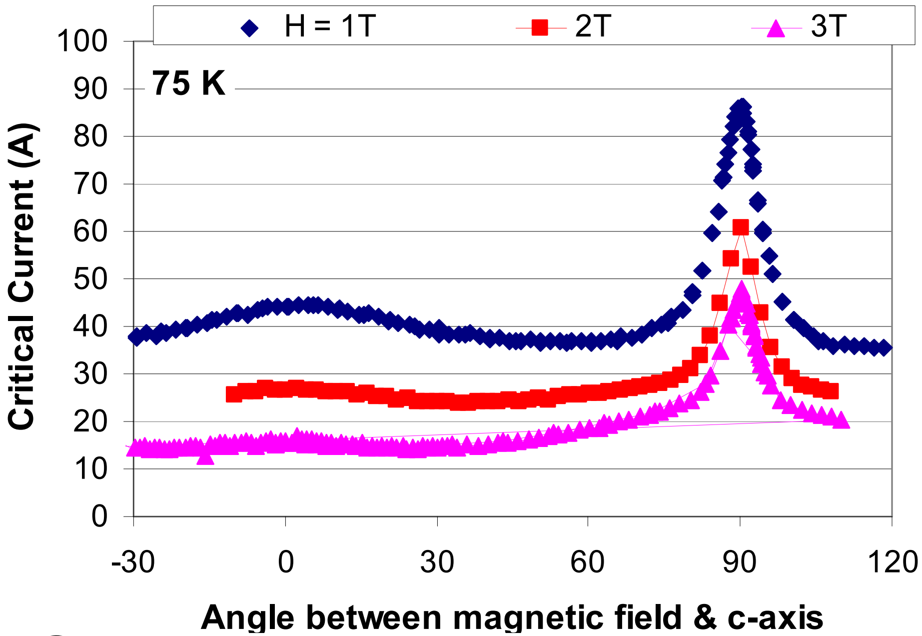
Los Alamos National Laboratory 1943 - 2003

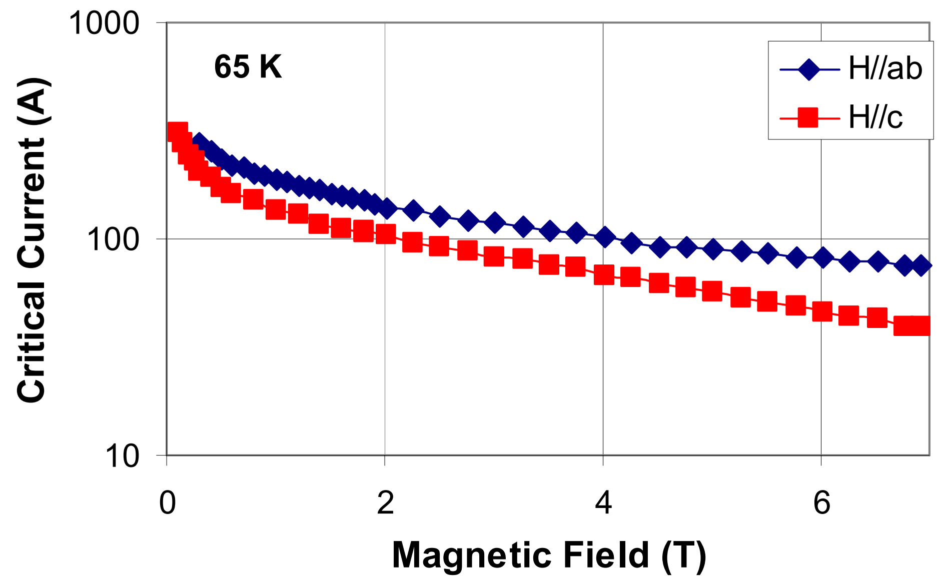
- Jc (0) = 1.23 MA/cm^2 ; 1.1 micron thick HTS

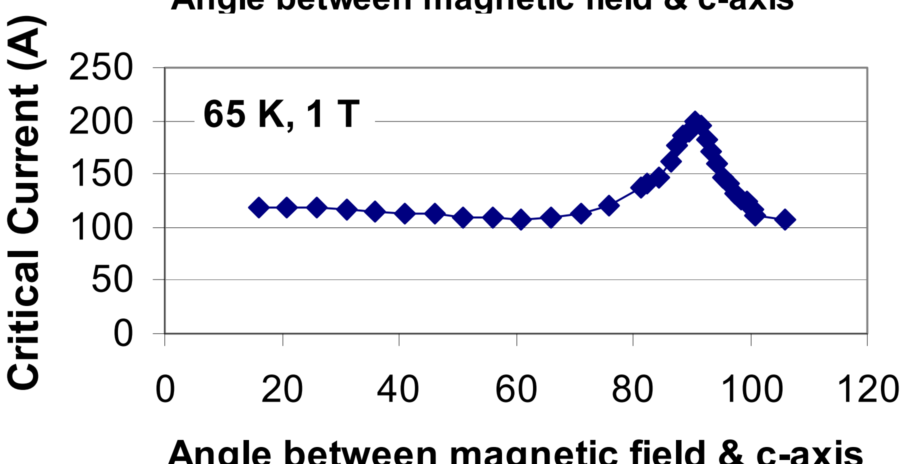
  Jc (1 T, B || c) = 0.343 MA/cm^2 --- (factor of _3.6 reduction_ !)

  To achieve this Jc at 1 T with a typical coated conductor, zero field Jc has to be about 2.5 MA/cm^2 to 3.5 MA/cm^2 !
- **Minimum Jc (1 T - any orientation) = 0.29 MA/cm^2 - (factor of *4.2 reduction* !)**
- Jc > 10^5 A/cm^2 even at 3.5 T

100 A at 2 T has been achieved at liquid nitrogen temperature !







Starting with a <u>1.7 micron thick, 167 A</u> tape at 77 K, zero field, we have at 65 K :

103 A at 2 T, B || c

135 A at 1 T, B || c

107 A at 1 T, any field orientation

306 A at 0.1 T, B || c

Important to further explore in-field performance of coated conductors

- **HTS conductors produced by *in-situ* processes could be favorably affected by possible flux pinning created by energetic species in the vapor phase.**

- ***Are HTS conductors produced by vapor phase techniques (in-situ process) perform differently in field than non-vapor phase (ex-situ process) produced HTS conductors ?***

- **All 100 A (zero field) coated conductors may not be created equal !**

- **Zero field performance may not present true capability of wire.**

- **Wire customer needs to compare in-field performance of coated conductors produced by different processes**

Scoring Criterion

- Research Integration

LANL-SuperPower collaboration is in its fourth year & going strong !

Successfully completed 3-year CRADA in February 2003.

Executed a 2-year follow-on CRADA in March 2003.

Electropolishing from Lab to Pilot Production : A successful research integration story

July	At last Peer review, LANL reported Electropolishing as a viable technique to polish substrates at high throughput and low surface roughness
Aug	
Sep	In late summer of 2002, SuperPower confirmed high Jc on their YBCO grown on their IBAD on LANL's electropolished substrates.
Oct	
Nov	In Fall 2002, SuperPower's Substrate scientist, Yunfei Qiao, learnt the electropolishing process at the Research Park with Vlad Mathias & Sascha Kreiskott. Soon afterwards, SuperPower designed their electropolishing rig with LANL's assistance.
Dec	
Jan	
Feb	In January 2003, SuperPower placed order for a Production-scale electropolishing rig.
Mar	
Apr	In Spring 2003, SuperPower scientist, Yunfei Qiao, spent more time at the Research Park working with LANL's electropolishing rig.
May	
June	In June 2003, electropolishing rig was delivered to SuperPower.
July	In July 2003, SuperPower produces 100 m electropolished tape, with quality similar to that achieved by LANL.

IBAD process has been successfully transitioned to a full-fledged Pilot operation

- IBAD process was successfully transitioned to SuperPower in the first CRADA.
- In FY'03, Paul Arendt of LANL assisted SuperPower in reducing IBAD layer thickness by a factor of 2.5 using concepts of low divergence ion beam conditions.
- In FY'03, LANL verified issues with SuperPower's IBAD process such as the "aperture effect". When SuperPower was optimizing their YBCO process, LANL qualified SuperPower's IBAD samples by depositing YBCO films under proven conditions.
- Work on transitioning IBAD MgO process has begun. SuperPower's IBAD scientist, Xuming Xiong, spent time at LANL to study the IBAD MgO process. SuperPower's Equipment Engineer, Ken Lenseth, visited LANL to design their prototype IBAD system for transitioning the IBAD MgO technology.

Close collaboration on HTS deposition

- Steve Foltyn visited SuperPower to assist in optimization of the PLD process using industrial laser & high deposition rates. Heater & Target Manipulator designs for high speed and long process time deposition were reviewed

- Several segments totaling about 3 m of IBAD MgO tape was provided to SuperPower to optimize their HTS deposition process. Using the feedback from SuperPower, LANL tailored the buffer structure for SuperPower's process.

- SuperPower has demonstrated Ic values of 100 – 147 A on 3-5 cm-long continuously-processed tapes on LANL's IBAD MgO.

Focussed & Goal-oriented advanced characterization of conductors to assist SuperPower

- SuperPower's Test & QC scientist Yi-Yuan Xie visited LANL to develop designs on *reel-to-reel critical current measurement* with Yates Coulter. SuperPower has established their own reel-to-reel Ic measurement system.

- Very close collaboration between SuperPower's Test & QC scientist Yi-Yuan Xie and Leonardo Civale of LANL to study *field and angular dependence* of SuperPower's coated conductors.

- SuperPower needed assistance in non destructive evaluation of variation in Ic across tape width in qualifying their tape slitting process. Tape patterning was used previously by SuperPower, but is not an option for slitting. LANL's technology of *Magnetic Imaging* developed by Fred Mueller was resurrected specifically to assist SuperPower. Very valuable data was obtained for SuperPower to determine the effect of Ic non uniformity vs. tape damage after slitting.

- Close collaboration between SuperPower's characterization scientist Jodi Reeves & LANL to study *microstructure development* especially using *Focussed Ion Beam Milling*.

SuperPower has benefited from partnerships with several other institutions too

SuperPower Inc.

- ANL : Continuing partnership on development of MOCVD.

  Raman Spectroscopy (Vic Maroni) to determine cause of Ic variation in 10+ m long tapes produced by MOCVD.

  TEM (Dean Miller) to understand rapid texture development in IBAD tapes produced in low divergent conditions.

  MOI (Ken Gray) to understand causes for Ic degradation in slit tapes
- AFRL-WPAFB : 3-year CRADA ; On-line plume diagnostics for PLD
- U.Albany : Contract for Advanced Characterization in its third year. Valuable data by FIB, TEM, AFM, Auger, XPS, microprobe.
- ORNL : 2-year CRADA executed in November ‘02
- NIST : Axial strain dependence of Jc on SuperPower tapes (Ekin, Chaggour)
- U.Kansas : AFOSR project on ion milling experiments on thick MOCVD and PLD films (Judy Wu).
- FSU: Beginning project of coupled MOI and stress-strain measurements (Justin Schwartz).

UNIVERSITY AT ALBANY
STATE UNIVERSITY OF NEW YORK

UT-BATTELLE

NIST

KU

NHMFL

Scoring Criterion

- FY'03 Performance vs. FY'03 goals
- FY'03 Results
- How we responded to FY'02 reviewers' comments
- FY'04 Plans

Scoring Criterion : FY'03 Performance vs. Plans

- Improve performance in meter-long conductors
  - ✓ Improved performance of meter-long MOCVD tapes from 90 A to 173 A.
  - ✓ Improved performance of meter-long PLD tapes from 43 A to 135 A.
- Modify substrate, buffer, and YBCO deposition facilities to scale up coated conductor fabrication to 10 - 100 m lengths.
  - ✓ Electropolishing rig set up to produce 100+ m lengths
  - ✓ Helix system installed in IBAD facility to produce 10 - 100 m lengths
- Demonstration of 10 - 100 m long substrate, buffer, and YBCO tapes with uniform performance over entire length.
  - ✓ 100+m long substrates polished by Chemical Mechanical Polishing & by electropolishing with surface roughness of 1 - 2 nm
  - ✓ 30 m long IBAD tape produced with uniform texture of 12 degrees
  - ✓ 10 m long YBCO tapes produced with end-to-end performance over 100 A by both MOCVD & PLD.
  - ✓ 18 m long YBCO tape produced by MOCVD with performance of 111 A

Scoring Criterion : FY'03 Performance vs. Plans (contd.)

- ❖ Demonstrate increase in throughput in all fabrication steps.
  - ✓ Increased throughput in polishing process by 6x.
  - ✓ Overall increase in throughput of IBAD process of 18x through use of helix system & reduction in IBAD layer thickness.
  - ✓ Increased MOCVD throughput by 5x using higher deposition rate
- ❖ Develop further QC tools for continuous off-line and on-line monitoring.
  - ✓ Breakthrough X-ray diffraction tool for continuous, rapid, in-plane texture measurement designed & constructed.
  - ✓ Reel-to-reel critical current measurement system constructed.
  - ✓ Reel-to-reel X-ray Fluorescence established for thickness measurements
  - ✓ Reel-to-reel capability established in Field Emission SEM

Scoring Criterion : FY'03 Performance vs. Plans (contd.)

- Continue defect analysis with various microstructural tools to provide feedback to process to enhance tape performance.
  - ✓ In addition to XRD, FESEM, & XRF in house we used FIB & TEM at U.Albany, Raman Spectroscopy & MOI at ANL, and MI at LANL to provide feedback to process to enhance tape performance
- Execute a follow-on CRADA to continue current collaboration with LANL & ANL.
  - ✓ Follow-on, 2-year CRADA executed with LANL
- Aggressive on MOCVD scale up with ANL.
  - ✓ Increased MOCVD group size by 67%
  - ✓ Commitment to MOCVD capital equipment in FY'03 : 34% of total capex (purchase of Pilot MOCVD facility)

Scoring Criterion : FY'03 Results

1. Performance enhancement in meter-lengths

- Problems with the substrate, IBAD, cap layer, and HTS layer that were limiting the performance of meter-lengths were identified.
- Performance of meter-long tapes was improved from 43 A to 135 A with PLD & 90 A to 173 A with MOCVD. 100+A tapes were reproducibly achieved by both high deposition rate processes. Ic up to 380 A in short samples.

2. Quality Control for long length processing

- Developed breakthrough design for tool for rapid, continuous, in-plane texture measurements. Texture measurement tool was constructed and data obtained over 20 m long tapes at 5x speed. Tool design is suitable for on-line texture measurement during the buffer deposition process.
- Reel-to-reel critical current measurement system constructed. Detailed measurements conducted in 5 cm step intervals to pin-point weak spots in 12 m long MOCVD tape.
- Reel-to-reel X-ray Fluorescence tool constructed for thickness & composition measurement over long tape lengths.
- Reel-to-reel capability installed in Field Emission SEM.
- Worked with ANL to use their reel-to-reel Raman Spectroscopy & MOI to determine cause of weak spots in 12 m MOCVD tape.

Scoring Criterion : FY'03 Results

3. Developments in high-throughput processing

- Production-scale electropolishing rig designed & procured.
  100 m long substrate tapes polished with new electropolishing rig. Surface roughness of 1.7 nm (comparable with Chemical Mechanical Polishing) was obtained over 100 m produced within 6 hours (6x faster).
- Helix tape handling system installed in Pilot IBAD system. Tape performance was optimized over 7 tape wraps. Also, high quality performance was obtained with 0.6 micron IBAD layers, 2.5 times thinner than before. A combination of helix system & thinner buffers led to 18 times increase in throughput.
- Achieved critical currents up to 147 A with IBAD MgO provided by LANL.
- Increased deposition rate with MOCVD to 80 Angstroms/second, without any photo-assist, and only by increasing precursor flow rate. Trend shows even higher deposition rates are possible by just increasing precursor flow rate. At this rate, demonstrated 100 A performance with a tape speed of 5 m/h in our research MOCVD system (5x throughput).
- Demonstrated reduced process cycle times with both MOCVD & PLD. Also, demonstrated that MOCVD process run can be stopped & restarted without loss in performance.

Scoring Criterion : FY’03 Results

4. Processing of longer lengths

- Solved texture variation problem with long tape lengths with helix system in Pilot IBAD facility to produce 30 m long tapes with uniform in-plane texture of 12 $\pm$ 0.7 degrees.
- Produced 30 m long IBAD tape with uniform in-plane texture of 12 degrees
- Reproducibly demonstrated 100 A performance over 10 m lengths
- Achieved 111 A over 18 m with MOCVD.

Scoring Criterion : FY'03 Results

5. Practical Conductor Development

- A new electroplating process was developed for copper stabilizer application. Demonstrated overloading 3 times critical current without loss in performance. *Advantages of electroplating includes rounded edges, double sided coatings and complete side wall coverage all in one pass*.

- Slitting of fully-processed coated conductor tapes to 4 mm widths demonstrated with less than 10% degradation in performance. Magnetic Imaging with LANL & MOI with ANL to discern role of parent tape non uniformity prior to slitting.

- Demonstrated 0.6% tensile bend strain in unreinforced tapes with 100% retainage of critical current. *HTS layer in these tapes were 9 times farther away from the neutral axis than it is from the tape surface*.

- 2 times superior performance shown in SuperPower tapes in a magnetic field of 1 T. Drop in critical current at 1 T is less than a factor of 4 in the B || c orientation compared to a factor of 7 to 10 in a typical coated conductor. Superior performance shown in intermediate field orientations too (a drop of about 4 at 1 T demonstrated in intermediate orientations).
  Jc performance at B || c can be modified by tailoring the HTS layer composition. Ic over 100 A demonstrated at 2 T, 65 K (B || c) starting with a typical HTS film thickness (1.7 microns).

How we responded to FY'02 reviewers' comments

"More emphasis on MOCVD process"
"Increase efforts on MOCVD"
"Recommend more emphasis to the promising MOCVD deposition"

- Increased MOCVD group size by 67%
- Commitment to MOCVD capital equipment in FY'03 : 34% of total capex (purchase of Pilot MOCVD facility)

"Focus on speeding up IBAD process"

- Helix system used to increase throughput by 7x
- Thinner buffer layers used to increase throughput further by 2.5x
- Procured equipment for retrofit of Pilot IBAD facility to increase throughput further by 3x
- Begun transitioning IBAD MgO technology from LANL

"Consider working with LANL on electropolishing of substrates"

- Not just considered, but, implemented electropolishing at SuperPower !

"Remain focused on scaling up the conductor process".

- We were and we will continue to be !

Scoring Criterion : FY’04 Plans

- Modify existing Pilot facilities and add new Pilot facilities for IBAD, Buffer, HTS deposition, and Stabilizer to produce 100 m lengths.
- Demonstrate at least 50 A over 100 m.
- Demonstrate linear speed greater than 10 m/h in every processing step to produce 100 A conductor.
- Modify and add QC tools for rapid reel-to-reel measurements over 100 m lengths.
- Transition IBAD MgO technology from LANL.
- Scale up a high rate IBAD process to produce 100 A conductor in at least meter lengths in Pilot facilities.
- Continue to build on progress with performance of conductor in high magnetic fields, mechanical strain, and electrical stabilization.
- Develop slitting technology to produce 1 - 10 m long conductors in 4 mm width with at least 100 A/cm performance.
- Provide several 10 m single piece lengths of 4 mm wide conductor to SEI (our cable partner) for construction of prototype second-gen cable.